Ecosystem Health

Science-Based Solutions

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

Report No. 1-10

Environment Canada
Environnement Canada

Canada

Science-Based Solutions
Solutions fondées sur la science

Prepared and published by
National Guidelines and Standards Office
Water Policy and Coordination Directorate
Environment Canada
Ottawa

August 2005

ISSN 1497-2689
ISBN 0-662-41160-9
Cat. No. En13-1/10-2005E-PDF

Scientific Supporting Document

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

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NOTE TO READERS

The *Ecosystem Health: Science-based Solutions* series is dedicated to the dissemination of scientific knowledge, information and tools for monitoring, assessing, and reporting on ecosystem health to support Canadians in making sound decisions. Documents published in this series include the scientific basis, methods, approaches and frameworks for environmental guidelines and their implementation; monitoring, assessing, and rehabilitating environmental quality in Canada; and, indicator development, environmental reporting and data management. Issues in this series are published *ad libitum*.

This particular issue provides the background information and rationale for the development of Canadian Environmental and Human Health Soil Quality Guidelines for benzene. For additional technical information regarding these guidelines, please contact:

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The Canadian Soil Quality Guidelines for benzene have been developed by the Soil Quality Guidelines Task Group of the Canadian Council of Ministers of the Environment (CCME). Environment Canada is both a member and the technical secretariat to this Task Group. These guidelines are included in the 2004 update to *Canadian Environmental Quality Guidelines*, which was originally published by the CCME in 1999. For CCME publications, please contact:

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This scientific supporting document is available in English only. Ce document scientifique du soutien n'est disponible qu'en anglais avec un résumé en français. Un sommaire de cette information technique est disponible en français sous le titre *Recommandations canadiennes pour la qualité de l'environnement* (CCME 1999).

Reference listing:

Environment Canada. 2005. Canadian Soil Quality Guidelines for the Protection of Environmental and Human Health: Benzene. Scientific Supporting Document. Ecosystem Health: Science-based Solutions Report No. 1-10. National Guidelines and Standards Office, Water Policy and Coordination Directorate, Environment Canada. Ottawa.

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ABSTRACT

This scientific supporting document provides the background information and rationale for the derivation of Canadian Soil Quality Guidelines for benzene for the protection of environmental and human health. Guidelines for this substance were originally published in 1999 by the Canadian Council of Ministers of the Environment (CCME) in *Canadian Environmental Quality Guidelines.* The benzene soil quality guidelines have since been revised to reflect new data and lessons learned during the development of the Canada-wide Standard for Petroleum Hydrocarbons in Soil (CCME 2000).

This document contains a review of information on the chemical and physical properties of benzene, a review of sources and emissions in Canada, the distribution and behaviour of benzene in the environment, and the toxicological effects of benzene on microbial processes, plants, animals and humans. This information is used to derive soil quality guidelines for benzene to protect both humans and ecological receptors in four types of land uses: agricultural, residential/parkland, commercial, and industrial. Development of these guidelines incorporated various modifications to the 1996 protocol (CCME 1996) that were used in the Canada-wide Standard for Petroleum Hydrocarbons in Soil (CCME 2000). These modifications included the derivation of guidelines for different soil textures (coarse and fine) and depths (surface soil and subsoil).

The Canadian Soil Quality Guidelines for the protection of environmental and human health for benzene in surface soil and subsoil, in coarse and fine soils on all land uses, as recommended by the Canadian Council of Ministers of the Environment, are presented below.

Canadian soil quality guidelines for benzene (mg·kg^{-1}).

	Surface soil		Subsoil	
	Coarse	Fine	Coarse	Fine
*10^{-6} incremental risk**				
Agricultural	0.0095	0.0068	0.011	0.0068
Residential/parkland	0.0095	0.0068	0.011	0.0068
Commercial	0.030	0.0068	0.030	0.0068
Industrial	0.030	0.0068	0.030	0.0068
*10^{-5} incremental risk**				
Agricultural	0.030	0.0068	0.030	0.0068
Residential/parkland	0.030	0.0068	0.030	0.0068
Commercial	0.030	0.0068	0.030	0.0068
Industrial	0.030	0.0068	0.030	0.0068

* Individual jurisdictions in Canada have different policies on whether to use 10^{-5} or 10^{-6} incremental cancer risks. Contact jurisdiction for guidance.

RÉSUMÉ

Le présent document contient une information de base ainsi qu'une analyse raisonnée pour l'élaboration des Recommandations canadiennes pour la qualité des sols concernant le benzène en vue de la protection de l'environnement et de la santé humaine. Les recommandations relatives à cette substance furent d'abord publiées en 1999 par le Conseil canadien des ministres de l'environnement (CCME) dans les *Recommandations canadiennes pour la qualité de l'environnement.* Elles ont par la suite été révisées afin de refléter l'ensemble des nouvelles données et des leçons tirées au cours du développement des Standards pancanadiens relatifs aux hydrocarbures pétroliers dans le sol (CCME 2000).

Ce document contient une revue de l'information sur les propriétés chimiques et physiques du benzène, une revue des sources et émissions au Canada, la distribution, le comportement dans l'environnement et les effets toxicologiques sur les processus microbiens, les plantes, les animaux et les humains. Cette information est utilisée pour l'élaboration des recommandations pour la qualité des sols relatives au benzène afin de protéger les récepteurs humains et écologiques dans quatre types d'utilisations des sols: agricole, résidentielle/parc, commerciale et industrielle. Plusieurs modifications du protocole de 1996 (CCME 1996) ont été incorporées à l'élaboration des nouvelles recommandations. Ces modifications incluent la dérivation de recommandations pour différentes profondeurs (surface et sous-sol) et textures du sol (grossier et fin).

Les recommandations canadiennes pour la qualité des sols en vue de la protection de l'environnement et de la santé humaine relatives au benzène pour le sol en surface et le sous-sol, pour les sols grossiers et fins et les quatre types d'utilisations des sols, telles que recommandées par le Conseil canadien des ministres de l'environnement, sont présentées ci-dessous.

Recommandations canadiennes pour la qualité des sols pour le benzène ($mg \cdot kg^{-1}$).

	Sol en surface		Sous-sol	
	Grossier	Fin	Grossier	Fin
Excès de risque de 10^{-6}				
Agricole	0,0095	0,0068	0,011	0,0068
Résidentiel/parc	0,0095	0,0068	0,011	0,0068
Commercial	0,030	0,0068	0,030	0,0068
Industriel	0,030	0,0068	0,030	0,0068
Excès de risque de 10^{-5}				
Agricole	0,030	0,0068	0,030	0,0068
Résidentiel/parc	0,030	0,0068	0,030	0,0068
Commercial	0,030	0,0068	0,030	0,0068
Industriel	0,030	0,0068	0,030	0,0068

* Chaque autorité compétente au Canada a sa propre politique différente concernant l'utilisation d'un excès de risque de cancer de 10^{-6} ou 10^{-5}. Pour obtenir des directives précises, il faut communiquer avec l'autorité compétente.

ACKNOWLEDGEMENTS

This scientific assessment for the development of Canadian Soil Quality Guidelines for benzene was prepared by Kelly Potter of the National Guidelines and Standards Office, Water Policy and Coordination Directorate of Environment Canada. It has been adapted from the 1999 supporting document for benzene soil quality guidelines (Environment Canada 1999) and from a report prepared by Komex International Ltd. for the Canadian Council of Ministers of the Environment (Komex 2002). Individuals involved in the preparation of the two source documents from which this document was adapted include: Marie-Chantal Bertrand, Mark Bonnell, Doug Bright, Glen Cain, Sylvie Coad, Philippa Cureton, Kristina Curren, Pam Dilworth-Christie, Ruth Fawcett, Christian Gagnon, Raju Gangaraju, Connie Gaudet, Carmela Grande, Victoria Laube, Luke Levesque, Jason Lin, Mike McFarlane, Heather McMurter, Stephanie Meakin, Vincent Mercier, Deborah Milne, Julian Moffat, Daniel Nadon, Stacey Norris, Sylvain Ouellet, Tracy Schneider, James Sevigny, Sherri Smith, Scott Teed, and Miles Tindal.

This document incorporates review comments received from various scientists representing federal and provincial government organizations, academic institutions, and the private sector. Thanks are extended to all those who provided input. In particular, the members of the CCME Soil Quality Guidelines Task Group are gratefully acknowledged for their scientific advice and reviews.

CHAPTER 1. INTRODUCTION

Canadian Environmental Quality Guidelines are intended to protect, sustain, and enhance the quality of the Canadian environment and its many beneficial uses. They are generic numerical concentrations or narrative statements that specify levels of toxic substances or other parameters in the ambient environment that are recommended to protect and maintain wildlife and/or the specified uses of water, sediment, and soil. These values are nationally endorsed through the Canadian Council of Ministers of the Environment (CCME) and are recommended for toxic substances and other parameters (e.g., nutrients, pH) of concern in the ambient environment.

The development of Canadian Soil Quality Guidelines was initiated through the National Contaminated Sites Remediation Program (NCSRP) in 1991 by the CCME Subcommittee on Environmental Quality Criteria for Contaminated Sites. In response to the urgent need to begin remediation of high priority “orphan” contaminated sites, an interim set of soil quality criteria was adopted from values that were in use in various jurisdictions across Canada (CCME 1991). Although the NCSRP program officially ended in March of 1995, the development of soil quality guidelines was pursued under the direction of the CCME Soil Quality Guidelines Task Group because of the continued need for national soil quality guidelines for the management of soil quality (with a particular focus on remediation of contaminated sites). Environment Canada serves as the technical secretariat to this Task Group.

Canadian Soil Quality Guidelines are developed according to procedures that have been described by the CCME (CCME 1996, 1997, and reprinted in 1999). According to this protocol, both environmental and human health soil quality guidelines are developed for four land uses: agricultural, residential/parkland, commercial, and industrial. The lowest value generated by the two approaches for each of the four land uses is recommended by the CCME as the Canadian Soil Quality Guideline. Guidelines for a number of substances were developed using this protocol and released in a working document entitled *Recommended Canadian Soil Quality Guidelines* (CCME 1997). The guidelines originally published in that document have since been revised and are now superseded by the Canadian Soil Quality Guidelines for the protection of environmental and human health published by the CCME in October of 1999 (CCME 1999). The interim soil quality criteria (CCME 1991) should be used only when soil quality guidelines based on the CCME protocol have not yet been developed for a given chemical.

This scientific supporting document provides the background information and rationale for the derivation of soil quality guidelines for benzene. This document contains a review of information on the chemical and physical properties of benzene, a review of sources and emissions in Canada, the distribution and behaviour of benzene in the environment, and the toxicological effects of benzene on microbial processes, plants, animals, and humans. In addition, the chapters describing the derivation of the environmental and human health soil quality guidelines for benzene include revisions made in 2002-2003 to the guidelines that were released in 1999 (CCME 1999). The revised recommended Canadian Soil Quality Guidelines for the protection of environmental and human health are also presented.

The Canadian Soil Quality Guidelines presented in this document are intended as general guidance. Site-specific conditions should be considered in the application of these values. The reader is referred to CCME (1999) for further generic implementation guidance pertaining to the guidelines. Soil quality guidelines are derived to approximate a “no- to low-” effect level (or threshold level) based only on the toxicological information and other scientific data (fate, behaviour, etc.) available for the substance of concern, and they do not consider socioeconomic, technological, or political factors. These non-scientific factors are to be considered by site managers at the site-specific level as part of the risk management process. Because these guidelines may be used and applied differently across provincial and territorial jurisdictions, the reader should consult the laws and regulations of the jurisdiction they are working within for applicable implementation procedures.

CHAPTER 2. BACKGROUND INFORMATION

Physical and Chemical Properties

Benzene (CAS #71-43-2) is a monocyclic aromatic compound with the chemical formula C_6H_6 and a molecular weight of 78.11. Synonyms for benzene include benzol, carbon oil, coal naphtha, light oil, phene, and phenyl hydride (Slooff 1988). The physical and chemical properties of benzene are listed in Appendix I.

Benzene is a clear, colourless inflammable liquid with a sweet, aromatic odour (Slooff 1988; Budavari 1989). Benzene is readily miscible with alcohol, chloroform, ether, carbon disulphide, carbon tetrachloride, glacial acetic acid, acetone and oils (Budavari 1989). It is relatively soluble in water, with a reported solubility of 0.174 to 0.187 $g \cdot 100\ mL^{-1}$ (at 25°C) (Shiu *et al.* 1990). Benzene has a relatively low octanol/water partition coefficient, in the order of 1.56 to 2.15, depending on temperature, pH and pressure (Hansch and Leo 1979).

Analytical Methods

In a review of monitoring methods for benzene, Slooff (1988) indicated that determination of benzene concentrations in surface water and air was very reliable, whereas determination from contaminated soil was much more variable. Much of this variability arises from the volatility of benzene, along with matrix effects, and may potentially present difficulties if targeted environmental standards or objectives approach the limits of quantitation (Maynard 1992).

Methods recommended for the analysis of benzene in soil by the CCME include U.S. EPA Methods 8240B, Rev. 2, and 8260A, Rev. 1 (CCME 1993). Method 8240B, Rev.2, *Volatile Organics by Gas Chromatography/Mass Spectrometry (GC/MS): Packed Column Technique*, is suitable for the analysis of nearly all types of samples, regardless of water content, including groundwater, aqueous sludges, soils, and sediments. The detection limit for benzene is 5 $\mu g \cdot kg^{-1}$ soil with a range of 5 to 600 $\mu g \cdot kg^{-1}$. The accuracy and precision of this method was not listed (CCME 1993). Method 8260A, Rev. 1, *Volatile Organics by Gas Chromatography/Mass Spectrometry (GC/MS): Packed Column Technique*, is also applicable to nearly all types of samples, regardless of water content, including groundwater, soils, and sediments. The detection limit for benzene is 0.04 $\mu g \cdot L^{-1}$ with a mean accuracy of 97% of true value and a precision of 5.7% relative standard deviation. For further details, please refer to the CCME (1993) publication.

Production, Uses, and Sources

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 1991). Estimates of emissions to the Canadian environment from these sources were not found. However, these natural sources are, reportedly, small compared to anthropogenic emissions (Slooff 1988), and non-anthropogenic 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 anti-knock agent. An estimated 3.9×10^{10} L of gasoline were sold in Canada in 2002 for use in road motor vehicles (Statistics Canada 2003).

The most detailed account of anthropogenic benzene emissions in the Canadian environment is provided by Jacques (1990) for the year 1985. Emissions in that year were estimated to total 34.1 kt. Nearly three-quarters (75.8%) originated from fuel combustion, in gas-powered light vehicles (61.0%), heavy vehicles (5.3%), water vessels (2.05%), aircraft (0.84%), trains (0.23%), other diesel-powered vehicles (1.4%) and other off-road usage (5.1%). Emissions from chemical manufacturing and benzene production accounted for 7.7% and 6.5% respectively. The remaining emissions were distributed among a number of other sources, including incineration of wastes, leaking underground storage tanks, and oil spills (Jacques 1990).

Changes in gasoline formulations to reduce benzene content and use of fuel-efficient vehicles or natural gas-powered vehicles were considered to have the greatest impact in reducing benzene emissions to the environment. A marked decrease in benzene emissions has been noted since 1975, and as of 1990, approximately half the 1975 emission levels was projected to be reached by the year 2000 (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).

Sources of benzene in soil include deposition from the atmosphere, leaking 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 have the potential to be 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.

Contamination of surface water may result from spills of chemicals and petroleum products and from discharges of industrial and municipal effluents (Slooff 1988). Estimates of total environmental loadings from such sources in Canada are not available.

Levels in the Canadian Environment

Air

Benzene discharged to the atmosphere has very little potential for entering other media. Level III fugacity model, with air, water, soil and sediment compartments, predicts that from all benzene released directly to the atmosphere, 99% will remain in the atmosphere at steady state (Mackay et al., 1992).

Mean concentrations of benzene in 586 samples of ambient air in ten Canadian cities surveyed between 1988 and 1990 ranged from 1.2 to 14.6 $\mu g \cdot m^{-3}$, with a maximum 24-hour average concentration of 41.9 $\mu g \cdot m^{-3}$ and an overall mean concentration of 4.4 $\mu g \cdot m^{-3}$ (Dann 1991). Similar levels were reported in a more recent survey of eleven Canadian cities, while mean concentration of benzene in three rural locations ranged from 0.6 to 1.2 $\mu g \cdot m^{-3}$ (Dann and Wang 1992). Airborne concentrations of benzene at the perimeter of gasoline service stations in five Canadian cities averaged 439 $\mu g \cdot m^{-3}$ (maximum of 6834 $\mu g \cdot m^{-3}$) in the summer of 1985 and 1383 $\mu g \cdot m^{-3}$ (maximum of 16 246 $\mu g \cdot m^{-3}$) in the winter of 1986 (PACE 1988). Mean short-term (10 to 15 minutes) airborne concentrations during refuelling ranged from 2600 to 4400 $\mu g \cdot m^{-3}$ (PACE 1988).

Soil

Level III fugacity model, with air, water, soil and sediment compartments at steady state, predicts that from all benzene released into soil, about 20% will be transfered to the atmosphere, less then 2% will be in water, less than 1% into sediments, and 77% will remain into the soil (Mackay et al., 1992).

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

Soil samples collected throughout Ontario from undisturbed old urban and rural parklands not impacted by local point sources of pollution were analyzed for a variety of chemicals to determine average background concentrations known as "Ontario Typical Range" (OTR). The 98th percentile of this data distribution (OTR_{98}) may be considered as the background level. For benzene, the OTR_{98} value for old urban parkland use was established at 0.047 $\mu g \cdot kg^{-1}$ soil while a concentration of 0.040 $\mu g \cdot kg^{-1}$ soil was obtained for rural parkland (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 $\mu g \cdot kg^{-1}$ dry soil. Roughly two-thirds of the soil samples contained benzene levels below detection limits (2 $\mu g \cdot kg^{-1}$ dry soil) (Environmental Science and Engineering 1991).

Groundwater

Slaine and Barker (1990) reported the presence of naturally occurring benzene in groundwater which may have been leached from bituminous layers of shale that were embedded in limestone near Belleville, Ontario. Benzene concentrations were commonly in the 50 to 200 $\mu g \cdot L^{-1}$ range with a maximum contaminant concentration of 500 $\mu g \cdot L^{-1}$. Cores of this material produced leachates with up to 86 $\mu g \cdot L^{-1}$ benzene.

Novakowski and Lapcevic (1988) reported a benzene concentration of 0.02 $mg \cdot L^{-1}$ from the groundwater of the Rochester Shale Formation near Niagara Falls, Ontario. Barker et al. (1988) also reported naturally occurring BTX (benzene, toluene and xylenes) in shale elsewhere in the Niagara Peninsula of southern Ontario.

Sediments

Benzene has been detected in $ng \cdot g^{-1}$ quantities in sediments (Health and Welfare Canada 1979). Benzene was absent from sediments receiving discharges from a nearby petroleum refinery, although it was measured in the refinery effluent, suggesting that benzene would be unlikely to accumulate in sediments (deFur et al. 1987). However, benzene was measured at 8.0 and 21 $ng \cdot g^{-1}$ (wet weight) in two sediments in Louisiana, but was not detected in a third sediment sample (Ferrario et al. 1985)

Surface water

Benzene concentrations in surface water are generally low. Results from several surveys summarized in CCREM (1987) for several locations in Ontario and in the St-

Lawrence River ranged from non-detectable (quantitation limits not given) to 5 $\mu g \cdot L^{-1}$. Benzene was reported undetectable in 17 of 23 plant effluents discharged into the St Clair River, Ontario, while other effluents contained benzene in the $\mu g \cdot L^{-1}$ range (Health and Welfare Canada 1979).

Biota

Data on the concentrations of benzene in living organisms in Canada were not found. In a study of sediments from Louisiana with benzene concentrations of 8 and 21 $ng \cdot g^{-1}$ (wet weight), concentrations of 220 and 260 $ng \cdot g^{-1}$ (wet weight) were detected in oysters and clams, respectively, while no concentrations were detected in clams collected from another site where sediments were free of benzene (Ferrario et al. 1985).

There have been reports that some foods contain benzene (Health and Welfare Canada 1979; Slooff 1988). For example, benzene has been detected as a volatile constituent of dry red beans, baked potatoes, and fresh and processed tomatoes (Buttery et al. 1975; Coleman et al. 1981; Chung et al. 1983). There are no indications in these reports whether benzene occurred naturally in these foods, or whether it was taken up from the environment.

Existing Criteria and Guidelines

A summary of existing soil and groundwater criteria and guidelines for benzene in various jurisdictions is provided in Appendix II.

CHAPTER 3. ENVIRONMENTAL FATE AND BEHAVIOUR

The four primary processes that control the fate and behaviour of benzene in the environment are:

- evaporation or volatilization into the gas phase coupled with diffusive transport in the gas phase;
- sorption to soil, particularly to organic matter;
- biodegradation;
- leaching by rainwater infiltrating through the unsaturated zone and/or dissolution in groundwater.

Soil

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. 1985b; 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. Downward migration will continue until the volume spilled equals the volume retained within the unsaturated zone, or until the plume reaches the 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

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 which 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 less than 2 days (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 one year, the calculated mass balances were 34.3% volatilized, 38.6% degraded, and 27.1% remaining 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 days 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 one year.

Sorption

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, albeit to a much lesser degree (Rutherford and Chiou 1992). The effect of temperature on the partitioning of benzene has not been reported.

Microbial degradation

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 (Rosenberg and Gutnick 1981; 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).

Biodegradation is probably also responsible for the removal of benzene deposited from the atmosphere. This is the most plausible explanation for its virtual absence in soils exposed to atmospheric benzene.

Leaching

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.

Water and Sediments

Groundwater

During a heavy gasoline spill, benzene will remain largely as an organic liquid and will not sorb extensively to soil (Slooff 1988). Consequently, depending on the soil porosity, the depth to the water table and the volume of the spill, the organic liquid will percolate to the water table, where it will float. Alternatively, it may settle on an impermeable stratum, such as a clay lens, and begin spreading laterally. Either way, this plume of free-hydrocarbon constitutes a reservoir from which the benzene may dissolve in the groundwater.

Once benzene is dissolved in groundwater, it will behave quite differently from benzene in the unsaturated zone. Volatilization from groundwater is considered to be negligible (Zoeteman et al. 1981). Thus, biodegradation becomes more significant as a removal process for dissolved benzene. However, the combined effects of high oxygen-demand (from the organic contaminant load) and poor oxygenation frequently result in the depletion of oxygen and macronutrients (nitrogen and phosphorus) within the plume of dissolved hydrocarbons (Barker et al. 1989; Thomas et al. 1990). Under these conditions biodegradation tends to be restricted to the fringes of the contaminant plume where groundwater supplies the required oxygen and macronutrients (Chiang et al. 1989). Thus, the two most significant removal processes in the unsaturated zone are considerably diminished in groundwater.

Dissolved benzene migrates with groundwater more readily than many organic contaminants (Mackay et al. 1985b). Some retardation relative to dissolved anions will arise due to reversible sorption onto soil organic carbon (Tucker et al. 1986; Barker et al. 1989). In one case study, the migration of benzene in a sandy aquifer with 0.02% organic carbon was 90% of the velocity of dissolved chloride (Barker et al. 1989).

Studies of gasoline components migrating in groundwater indicated that distances travelled were in the order of 10 to 300 $m \cdot a^{-1}$ (Barker et al. 1989; Chiang et al. 1989; Jackson and Patterson 1989; Cozarelli et al. 1990; Turney and Goerlitz 1990; Barbaro et al. 1991). Benzene was consistently attenuated in oxygenated areas, as might be expected for conditions favouring biodegradation (Barker et al. 1989; Chiang et al. 1989). In contrast, biodegradation was absent in an anaerobic sandy aquifer (Barbaro et al. 1991), but was apparent in a shallow, anaerobic and methanogenic glacial-outwash aquifer (Cozarelli et al. 1990). This field evidence is consistent with a laboratory study on benzene biodegradation under methanogenic conditions (Wilson and Rees 1986).

Thus, under certain conditions (anaerobic groundwater, low volatilization) it is possible for benzene to migrate over relatively long distances with little reduction in concentration. In addition, laboratory studies, supported by field observations, indicate that benzene is usually among the last to be degraded in a mixture of simple aromatic and phenolic compounds (Meyer et al. 1984; Arvin et al. 1989). It has also been reported that biodegradation decreases considerably, or ceases altogether, when benzene concentrations are below 100 $\mu g \cdot L^{-1}$ (Tucker et al*.* 1986). Under the above conditions, ecological damage to surface waters from discharges of benzene-contaminated groundwater represents a significant threat.

Surface Water and Sediments

While petroliferous seeps are naturally occurring sources of benzene in water or sediments, the major sources are expected to be anthropogenic, from effluent discharges or from spills (Merian 1982). Benzene is not expected to be retained in surface waters, despite its solubility, because it will readily evaporate (Merian 1982; Slooff 1988). In a detailed study of the fate and persistence of VOCs in seawater, Wakeham et al*.* (1983) calculated half-lives for benzene at 3.1 days in the summer (20–22°C, average temperature), 13 days in the winter (3–7°C, average temperature), and 23 days in the spring (8–16°C, average temperature). The data indicate that volatilization is the predominant removal process, but that biodegradation can also account for some of the loss. The potential for biodegradation is variable and partly reflects past exposure to benzene and nutrient levels in the water (Vaishnav and Babeu 1987). This variation probably results from the selective stimulation of benzene-degrading bacteria and is probably a significant factor in soils and groundwater as well (Lindstrom et al*.* 1991; Madsen et al*.* 1991).

Although sediments are expected to retain benzene in proportion to their organic carbon content, it is not frequently detected in sediments (Karickhoff et al*.* 1979). Aside from the expected loss to the water column, some biodegradation would be expected in the surface sediments. However, anaerobic biodegradation is insignificant, suggesting that benzene associated with bituminous blobs may be persistent (van Beelen and van Keulen 1990).

Air

The fugacity models developed by Mackay and colleagues predict that benzene will always have a tendency to migrate to the atmosphere (Mackay et al*.* 1985a; Mackay et al*.* 1992). However, benzene does not accumulate in the atmosphere because it is rapidly oxidized by hydroxy (OH) radicals (Doyle et al*.* 1975; Darnall et al*.* 1976). According to Slooff (1988), the products of this reaction are principally phenol and ring opening products such as glyoxal and formaldehyde. By comparison, benzene is largely unreactive with ozone, which is more abundant in the atmosphere (Atkinson and Carter 1984). The half-life of benzene in the atmosphere has been estimated to range from 2.4 to 24 hours (Doyle et al. 1975; Darnall et al. 1976).

CHAPTER 4. BEHAVIOUR AND EFFECTS IN BIOTA

The available information on the toxicological effects of benzene on soil microbial processes, terrestrial plants and invertebrates, as well as mammals and birds has been reviewed and summarized in this chapter in support of the derivation of environmental soil quality guidelines. This information has been tabulated in Appendices III and IV as either "consulted" studies (i.e., those studies which were reviewed but not used in the derivation of guidelines) or "selected" studies (i.e., those studies which met the screening procedures for use in the derivation of guidelines, as described in Chapter 6).

Soil Microbial Processes

Metabolic Fate and Behaviour

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).

Toxicity

Effects of applying benzene at concentrations of 1000 $\mu g \cdot g^{-1}$ dry soil on bacterial respiration have been examined in two soils (Walton et al. 1989). No effects were observed in Captina silt loam, whereas a transient decrease in respiration occurred in McLaurin sandy loam. However, respiration rates after 6 days were not significantly different from controls in both cases, 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) recently 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

Metabolic Fate and Behaviour

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).

Toxicity

Plant toxicity studies selected for use in soil quality guidelines derivation are presented in Appendix IV, while additional plant studies that were consulted but not used in guideline derivation are presented in Appendix III.

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).

Several phytotoxicity tests, including 3-day seedling emergence and root elongation tests for radish (*Raphanus sativus*), and 5-day seedling emergence and root elongation tests for lettuce (*Lactuca sativa*) were conducted by Environment Canada (1995) (Appendix III). The lowest benzene concentrations at which adverse effects occurred were 24 and 40 $mg{\cdot}kg^{-1}$ for radishes and lettuce, respectively, resulting in a 25% reduction in seedling emergence. Although these results 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). Due to these concerns, the data were not selected for use in deriving the most recent guidelines.

With significant advances in techniques for determining the toxicity of highly volatile compounds, new plant toxicity tests were conducted by ESG International in 2002 (Appendix IV). 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 soil. In coarse soils, the most sensitive endpoint for alfalfa was reduction of root dry mass with an IC_{25} value of 235 $mg{\cdot}kg^{-1}$, and for northern wheatgrass the most sensitive endpoint was an IC_{25} of 73 $mg{\cdot}kg^{-1}$ for reduction of root dry mass (ESG 2002b). The results for fine soils reported by ESG (2002b) 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

Metabolic Fate and Behaviour

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 (eg., *Fucus* sp.) to molluscs (eg., *Mytilus edulis*) to fish (eg., *Oncorhynchus kisutch*) (Malins 1977).

Toxicity

Toxicity tests with nematodes or earthworms have typically been conducted in solutions containing soil extracts or with a contact filter paper test from which an effective soil concentration cannot readily be calculated. However, Hartenstein (1982) reported that benzene dissolved in sludge (approximately 13% solids) applied to a 4 mm layer of silt loam significantly affected growth, but not survival, of the earthworm *Eisenia foetida* at a concentration of 8% (w/w).

Earthworm survival tests by Environment Canada (1995) are reported in Appendix III. In these tests, benzene concentrations as low as 161 mg·kg^{-1} were found to cause 25% mortality in the earthworm *Eisenia foetida*. The results were not considered acceptable for use in the guideline derivation procedure because of problems similar to those experienced in the phytotoxicological tests.

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 30 mg·kg^{-1}, respectively (ESG 2002b). The results reported by ESG (2002b) 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

Metabolic Fate and Behaviour

Some information is available on the metabolic fate of benzene in mammals, but much of this relates to human health (see Chapter 5). Information on the metabolism of benzene in livestock or wildlife species is lacking.

Toxicity

No studies on the toxic effects of benzene on livestock, mammalian wildlife, or birds have been found.

Bioaccumulation

There are no reports of benzene bioaccumulation in terrestrial animals. However, 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 days), whereas longer exposure periods (>33 days) 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 14C-labelled benzene formed 62% $^{14}CO_2$ within 1 week (Scheunert and Korte 1986).

CHAPTER 5. BEHAVIOUR AND EFFECTS IN HUMANS AND MAMMALIAN SPECIES

Metabolic Fate and Behaviour

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.

Human and Experimental Animal Health Effects

Acute Toxicity

With a log K_{ow} of 2.13, benzene will readily be taken up into the cell membrane. Nonreactive and nonionic industrial chemicals with log K_{ow} values in this range have a broad toxic action designated Narcosis I (Schultz et al. 1989). This designation is widely used in predictive toxicology to describe compounds producing non-specific perturbation of the cell membrane and an overall depression of cellular metabolism. The general narcotic effects caused by the action of benzene on the membrane include:

- inhibition of nerve transmission and an overall depression of central nervous system function;
- inhibition of gas exchange and a lowered oxygen-binding capacity of haemoglobin;
- 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 $g \cdot m^{-3}$, measured as the 4-hour 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 sixty days 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 mouse (DBA/2) shows distinct sexual differences in the response to benzene. These researchers measured the effects of benzene inhalation on sister chromatid exchange (an indicator of mutagenesis) and on bone marrow cell proliferation. Exposure of mice to 10 $g \cdot m^{-3}$ benzene vapours for four hours caused a significant (~80%) increase in sister chromatid exchange in male and female mice. Pretreatment with phenobarbital, which increases mixed-function oxidase activity, led to a further increase in sister chromatid exchange in female, but not in male, mice. On the other hand, benzene significantly retarded bone marrow cell proliferation in male mice but not in female mice.

Chronic Toxicity

Much of the detailed information on the chronic toxicity of benzene to mammals was derived from studies on 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. Several toxic responses have been reported in mammals that result from the metabolism of benzene in solution in the aqueous phase, while the occurrence of benzene in lipid components has no reported chronic consequences (Manahan 1989).

Although the toxic modes of action of benzene follow several pathways (Manahan 1989), the major chronic effects of benzene are on the haematopoietic system (which includes the blood and the structures that function in its production). Chronic toxicity is considered to result from a metabolite because benzene is not a highly reactive molecule, and because experimental observations link mixed-function oxidase activity to its toxicity (Fishbein 1984; Manahan 1989; Andrews and Snyder 1991). This toxic component is probably benzene epoxide, formed by mixed function oxidase. Benzene epoxide is a reactive molecule with an affinity for nucleic acids and when bound together can lead to mutagenesis/carcinogenesis or cell death (Manahan 1989).

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, mice), the carcinogenicity of benzene shows a wide range of tissue and species sensitivity (Byard 1982), with the most common effect being tumerogenicity. Acute myelogenous leukaemia has not been observed in other mammals exposed to benzene (Andrews and Snyder 1991).

Influence of Environmental Factors

Two studies have indicated that the toxicity of benzene can be altered by the mode of exposure. Dermal application of the radioactive pure product or ^{14}C-benzene adsorbed to sandy soil produced similar high peak plasma concentrations and lower elimination rates compared with clay-bound ^{14}C-benzene (Skowronski et al. 1988). Tissue levels of radioactivity were significantly higher (48 hours following treatment) in treated skin and lower in fat for the clay-bound exposure. Force-feeding (gavage) of an aqueous suspension of soil-bound (sand or clay) radioactive benzene resulted in higher peak plasma concentrations of radioactivity than an equivalent dose from an aqueous solution (Turkall et al. 1988). However, administration of clay-bound benzene, and to a lesser degree, sandy soil-bound benzene, resulted in a statistically significantly higher rate of elimination of radioactivity from plasma. These matrix and exposure effects suggest that differences in bioavailability and tissue distributions could alter the toxicity of benzene in animals.

No information was found regarding the toxic effects of benzene at temperatures below its freezing point of 5.2°C. Low temperatures may result in a significant shift in the prevalence of the vapour phases of benzene. Given the winter temperatures in Canada, we lack information on potential toxicological risks from benzene pertinent to our climatic conditions.

CHAPTER 6. DERIVATION OF ENVIRONMENTAL SOIL QUALITY GUIDELINES

The derivation of environmental soil quality guidelines for benzene is outlined in the following sections for four land uses: agricultural, residential/parkland, commercial, and industrial. Various modifications to the CCME (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. Modifications include 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. These environmental soil quality guidelines for benzene will be considered along with the human health guidelines in making final recommendations for Canadian Soil Quality Guidelines for the protection of environmental and human health (CCME 1996; see Chapter 8).

The environmental soil quality guidelines for benzene are derived using the available toxicological data to determine the threshold level of effects for key ecological receptors. Exposure from direct soil contact is the primary derivation procedure used for calculating environmental quality guidelines for residential/parkland, commercial, and industrial land uses. Exposure from direct soil contact as well as soil and food ingestion is considered in calculating guidelines for agricultural land use, with the lower of the two values generated from these derivation procedures being recommended as the environmental soil quality guideline for this land use. In addition to these primary derivation procedures, check mechanisms are used to consider important direct and indirect soil exposure pathways, such as protection of groundwater for aquatic life and for livestock.

All data selected for use in the following derivations have been screened for ecological relevance and are presented in Appendix IV. Studies that have been consulted but not used in guideline derivation are presented in Appendix III. Studies were excluded from use because of one or more of the following reasons:

- soil pH was not recorded;
- soil pH was below 4 (as this is considered outside the normal pH range of most soils in Canada);
- no indication of soil texture was provided;
- inappropriate statistical analysis was used;
- test was not conducted using soil or artificial soil;
- test soil was amended with sewage sludge or a mixture of toxicants;

- test did not use controls.

Attempts to generate toxicological data by Environment Canada (1995) for use in the derivation of soil quality guidelines have demonstrated the problems associated with testing volatile organic compounds. Two tests were run for each VOC yet sampling and handling problems persisted. Generally the amount of VOC applied and the amount actually measured in the soil differed by an order of magnitude, which was considered unacceptable. Due to these problems, the data from Environment Canada (1995) were not used in deriving the environmental soil quality guidelines.

There were sufficient acceptable data available to meet the minimum data requirements described in the Protocol (CCME 1996) for the derivation of soil quality guidelines based on soil contact (SQG_{SC}). The available dataset was not sufficient to meet the minimum requirements of the protocol for calculating the soil and food ingestion (SQG_I); however, the process used to determine tolerable daily intakes for humans was adapted to calculate daily threshold doses for livestock. There were insufficient data available to calculate a nutrient and energy cycling check for any of the categories of land use.

Agricultural and Residential/Parkland Land Uses

Soil Contact

The derivation of the soil quality guideline for soil contact (SQG_{SC}) is based on toxicological data for vascular plants and soil invertebrates. The toxicological data for plants and invertebrates selected according to CCME (1996) are presented in Appendix IV.

ESG (2001, 2002a) conducted 14-day studies with both coarse and fine soils for two plant species, *Agropyron dasystachyum* (early northern wheatgrass) and *Medicago sativa* (alfalfa), and two invertebrate species, *Eisenia andrei* (earthworm) and *Onychiurus folsomi* (collembolan). Procedures were adopted to minimize the loss of volatile compounds from the test vessels. To determine the actual concentrations of benzene to which the organisms were exposed, chemical analyses were conducted immediately after the soils were spiked. However, organisms were not introduced to the soils until 2 hours later (plants) or 24 hours later (invertebrates). Therefore, further work was done to determine the amount of benzene that would have been lost from the soil between spiking and introduction of the organisms (ESG 2002b). Due to budget limitations, this work was conducted using the coarse artificial soil only. The information on benzene losses from coarse soils was used to adjust the estimates of the initial concentrations to which the organisms were exposed. The LC_{25}, IC_{25} and LOEC values based on nominal concentrations of benzene were converted to "estimated effect" LC_{25}, IC_{25} and LOEC values using regression equations based on the analysis of samples collected 2 hours (for plants) or 24 hours (for invertebrates) after spiking. For the fine field-collected soil, the regression equations were based on the analysis of samples collected immediately after soil spiking.

A modification was made to the ESG dataset prior to calculating the guidelines (Komex 2002). The “estimated effect” LC_{25}, IC_{25} and LOEC concentrations for the fine soil were recalculated using the 2 and 24 hour regression equations (for plants and invertebrates, respectively) for coarse soil, rather than the “time zero” regression equations for fine soil. It is expected that volatile losses in the period following spiking will be more rapid for the coarse soil than for the fine soil, and accordingly it was considered conservative to apply the 2 and 24 hour coarse soil regression equations to the fine soils.

There were sufficient toxicological data to use the preferred weight of evidence (WOE) method for guideline derivation. ESG (2002b) found that it was not possible to calculate meaningful LC_{25} values for the *Eisenia andrei* tests, based on the “all or nothing” nature of the data (i.e., little mortality was seen at the NOEC, and almost complete mortality was observed at the LOEC). Therefore, the EC_{25} Distribution WOE method could not be used. Instead, the Effects/No Effects Data Distribution WOE method was used, incorporating IC_{25} values for the northern wheatgrass and alfalfa, LC_{25} values for the collembolan, and LOEC values for the earthworm. The derivation of the SQG_{SC} followed a procedure modified from the Canada-wide Standard for Petroleum Hydrocarbons (CCME 2000). The procedure was as follows:

- For each distinct test/endpoint, only the data representing a 25% effect (e.g., LC_{25} or EC_{25}) were considered, with the exception of the earthworm tests for which the LOECs were considered;
- If tests differed only in duration, only the data for the longest duration were used;
- If multiple data were available for the same chemical, endpoint and species, these data were replaced by their geometric mean;
- For agricultural and residential/parkland land uses, the SQG_{SC} was calculated as the 25th percentile of plant and invertebrate data.

For the plant data, measurements of shoot dry weight and shoot wet weight for the same species were considered as multiple data and were therefore replaced by their geometric mean. Similarly a geometric mean was used to replace measurements of root dry weight and root wet weight for the same plant species.

Rank percentiles of the toxicity data distribution were plotted against the LC_{25} concentrations for coarse (Figure 1) and fine (Figure 2) soil.

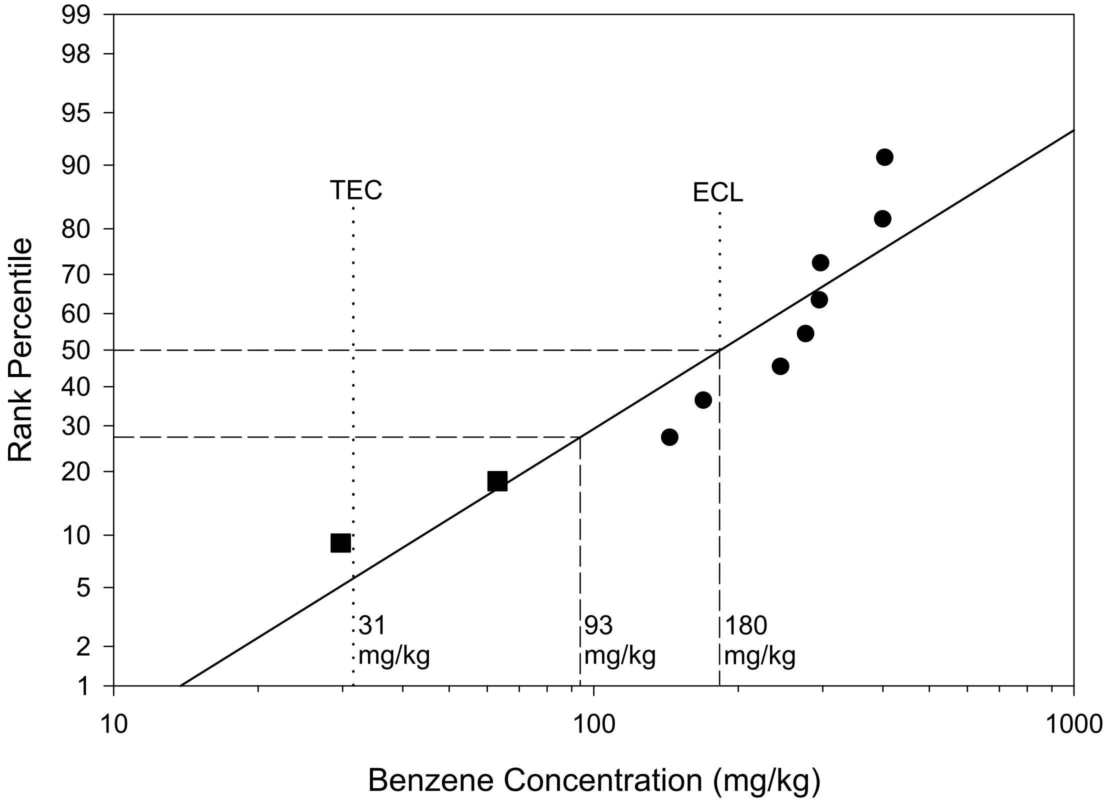

Figure 1. Rank percentile plot of toxicity data distribution for plants (●) and invertebrates (■) exposed to benzene in coarse soil.
TEC = threshold effects concentration
ECL = effects concentration low

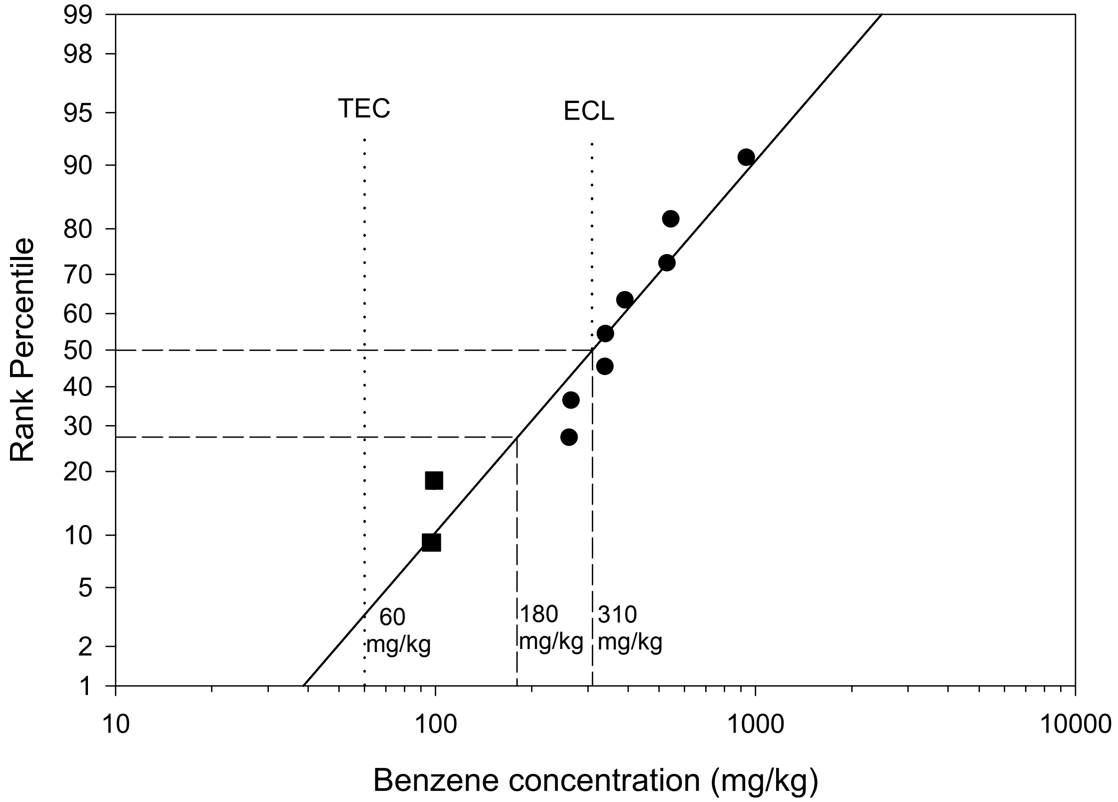

Figure 2. Rank percentile plot of toxicity data distribution for plants (●) and invertebrates (■) exposed to benzene in fine soil.
TEC = threshold effects concentration
ECL = effects concentration low

The 25th percentile of the rank distribution, as estimated from the graph, was chosen to represent the no potential effects range (NPER) for the agricultural and residential/parkland land uses. The TEC was calculated using the following equation:

$$\text{TEC} = \text{NPER} / \text{UF}$$

where,

TEC = threshold effects concentration ($mg \cdot kg^{-1}$)
NPER = no potential effects range (25th percentile of the distribution) ($mg \cdot kg^{-1}$)
UF = uncertainty factor (if needed).

An uncertainty factor was deemed necessary for two reasons:

1. only a limited number of species were represented in the data distribution
2. greater than 50% of the data for soil invertebrate toxicity falls below the 25th percentile of the distribution.

Therefore, an uncertainty factor of 3 was chosen. By applying this uncertainty factor, the resulting TEC falls at or below the lower of the two invertebrate data points for both the coarse and fine soils, indicating that the guideline should be sufficiently protective of invertebrates.

Using the above procedure, the surface soil SQG_{SC} value for both agricultural and residential/parkland land uses was calculated as 31 $mg \cdot kg^{-1}$ for coarse soils, and 60 $mg \cdot kg^{-1}$ for fine soils.

Subsoil guidelines for soil contact were calculated based on management decisions made in the PHC CWS (CCME 2000). In the PHC CWS, subsoil guidelines were between 2 and 6 times greater than surface soil guidelines, based on the lower biological activity levels at subsoil depths, but also taking into account other considerations such as aesthetics, safety, and underground infrastructure. For benzene, subsoil SQG_{SC} values for both agricultural and residential/parkland land uses were calculated as twice the corresponding surface soil guideline, i.e., 62 $mg \cdot kg^{-1}$ for coarse soils and 120 $mg \cdot kg^{-1}$ for fine soils.

Nutrient and Energy Cycling Check

A nutrient and energy cycling check could not be calculated due to insufficient data.

Soil and Food Ingestion

The soil quality guideline for ingestion (SQG_I) applies only to agricultural land use.

To calculate a guideline for this pathway, the CCME (1996) protocol requires the determination of a daily threshold effect dose (DTED) for livestock and grazing wildlife. A DTED is defined as a dose level below which adverse effects are not expected in a receptor. The minimum data requirements in the CCME (1996) protocol for calculating a DTED include at least one study on a grazing herbivore and one oral avian study. These data requirements were not met for benzene. The Soil Quality Guidelines Task Group of CCME felt that management of benzene would be better served by having guidelines for this exposure pathway than by having no guidelines, so an alternative protocol for estimating the DTEDs was adopted.

A DTED for benzene was developed for livestock by adapting the methodology used for calculating tolerable daily intakes (TDIs) for humans. Neither Health Canada nor the USEPA have published a human health tolerable daily intake or a reference dose for benzene. Both agencies focus on carcinogenic endpoints in deriving a human exposure limit for benzene. Carcinogenic endpoints are not normally considered in deriving guidelines for livestock. Therefore, an oral DTED for benzene in dairy cattle ($0.08\ mg \cdot kg^{-1}\ bw \cdot d^{-1}$) was derived based on the reported LOAEL (lowest observed adverse effect level) from a study by Hsieh et al. (1988). Mice were exposed to benzene in drinking water at doses ranging from 0 to 180 $mg \cdot kg^{-1}\ bw \cdot d^{-1}$ for 28 days (water concentrations ranged from 0 to 790 $mg \cdot L^{-1}$). The reported LOAEL, based on hematological anemia and immunological effects, was 8 $mg \cdot kg^{-1}\ bw \cdot d^{-1}$. A 100-fold uncertainty factor was applied, based on a 10-fold factor to account for the use of a LOAEL from a less than chronic duration study, and a further 10-fold factor to account for the uncertainties in extrapolating from one species to another.

$$DTED = \frac{8}{100} = 0.08\ mg \cdot kg^{-1}\ bw \cdot d^{-1}$$

An animal may be exposed to a contaminant by more than one route. Total exposure comes from a combination of contaminated food, direct soil ingestion, dermal contact, contaminated drinking water, and inhalation of air and dust. Exposure from all of these routes should not exceed the DTED. Assuming that drinking water, dermal contact and inhalation account for 25% of the total exposure (CCME 1996), the remaining 75% of exposure is attributed to the ingestion of food and soil. It follows then that exposure from soil and food ingestion should not exceed 75% of the DTED.

The soil ingestion rate was calculated as:

$$SIR = \frac{FIR \times PSI}{1 - PSI} = 1.674\ kg \cdot d^{-1}$$

where,

SIR = soil ingestion rate for dairy cattle;
FIR = food ingestion rate for dairy cattle ($18.5\ kg \cdot d^{-1}$; CCME 1999); and,
PSI = proportion of soil ingested by dairy cattle (0.083; default value from McMurter 1993).

Bioconcentration of benzene into livestock fodder is not expected to be significant, thus a guideline was calculated only for the livestock soil ingestion (and not food ingestion) pathway. The SQG_I was calculated, based on exposure to a dairy cow, using the following equation:

$$SQG_I = \frac{0.75 \times DTED \times BW}{SIR \times BF}$$

where,

SQG_I = soil ingestion guideline; concentration of the contaminant in soil that will not result in animals being exposed to greater than 75% of the DTED ($mg \cdot kg^{-1}$ soil);
DTED = daily threshold effect dose for livestock ($0.08\ mg \cdot kg^{-1}\ bw \cdot d^{-1}$);

BW = body weight for dairy cattle (701 kg);
SIR = soil ingestion rate for dairy cattle (1.674 kg·d^{-1}; calculated above); and,
BF = bioavailability factor (1; assumed).

Substituting these values into the above equation and rounding to 2 significant figures yields an SQG_I value of 25 mg·kg^{-1} for agricultural land use.

Commercial and Industrial Land Uses

Soil Contact

As for agricultural and residential/parkland land uses, the derivation of the SQG_{SC} for commercial and industrial land uses followed a procedure modified from the Canada-wide Standard for Petroleum Hydrocarbons (CCME 2000) (see description above). For commercial and industrial land uses, however, the SQG_{SC} was calculated as the 50th percentile of the plant and invertebrate data, also referred to as the effects concentration low (ECL). Using this procedure, the surface soil SQG_{SC} value for both commercial and industrial land uses was calculated as 180 mg·kg^{-1} for coarse soils, and 310 mg·kg^{-1} for fine soils (see Figures 1 and 2).

Subsoil guidelines for soil contact were calculated based on management decisions made in the PHC CWS (CCME 2000). In the PHC CWS, subsoil guidelines were between 2 and 6 times greater than surface soil guidelines, based on the lower biological activity levels at subsoil depths, but also taking into account other considerations such as aesthetics, safety, and underground infrastructure. For benzene, subsoil SQG_{SC} values for both commercial and industrial land uses were calculated as twice the corresponding surface soil guideline, i.e., 360 mg·kg^{-1} for coarse soils and 620 mg·kg^{-1} for fine soils.

Nutrient and Energy Cycling Check

A nutrient and energy cycling check could not be calculated due to insufficient data.

Final Environmental Soil Quality Guidelines

The final environmental soil quality guidelines (SQG_E) for benzene for the two soil textures and two soil depths in each of the four land uses are presented in Tables 2 and 3.

Agricultural Land Use

The lower value from the two pathways (SQG_{SC} and SQG_I) is selected as the final SQG_E for surface soils on agricultural lands. The lower of the two pathways is the SQG_I, therefore the final SQG_E for both coarse and fine surface soils on agricultural lands is 25 mg·kg^{-1}. Soil ingestion by livestock is not an applicable pathway for subsoils, so the

SQG_E is equal to the SQG_{SC}. Therefore, the final SQG_E values for coarse and fine subsoils on agricultural lands are 62 and 120 $mg \cdot kg^{-1}$, respectively.

Residential/Parkland Land Use
The SQG_{SC} values of 31 and 60 $mg \cdot kg^{-1}$ for coarse and fine surface soils, respectively, and 62 and 120 $mg \cdot kg^{-1}$ for coarse and fine subsoils, respectively, are the final SQG_E values for residential/parkland land use.

Commercial and Industrial Land Uses
The SQG_{SC} values of 180 and 310 $mg \cdot kg^{-1}$ for coarse and fine surface soils, respectively, and 360 and 620 $mg \cdot kg^{-1}$ for coarse and fine subsoils, respectively, are the final SQG_E values for commercial and industrial land uses.

Groundwater Checks

Soils are hydrologically linked to groundwater systems. A major concern with soil contamination is that it can and does lead to groundwater contamination. Two checks, (one for the protection of aquatic life, and one for the protection of livestock watering) were calculated to determine maximum soil concentrations of benzene that will not result in unacceptable transfers of contaminants to groundwater. These check values were not used in determining the national soil quality guidelines, but are provided as a reference for site-specific application in areas with underlying groundwater systems.

Protection of Groundwater for Aquatic Life

Prudent assumptions are that an aquifer underlying a remediated site may have the potential to enter surface water bodies. Therefore, the following equations are used to calculate the concentration in soil that will not cause groundwater concentrations to exceed existing water quality guidelines for the protection of freshwater aquatic life. The groundwater check follows the rationale and calculation procedure from the PHC CWS (CCME 2000). Aquatic life groundwater check values are the same for all land uses and for both surface soil and subsoil.

The check value for this pathway is based on the concentration of dissolved benzene at a distance of 10 metres from the source, and at a time of 100 years after the benzene was introduced to the soil. A check value has not been calculated for fine soils because a groundwater migration calculation using parameters for fine soil shows that in 100 years, groundwater does not flow 10 metres. It should be noted, however, that if making Tier 2 calculations at a site where the protection of this groundwater pathway is active, a hydraulic conductivity of 32 metres per year should be assumed, if adequate measured data are not available.

The calculation of the groundwater check is based on the Canadian water quality guideline for benzene for the protection of aquatic life (CCME 1999) and a dilution factor calculated for each of four processes:

1. partitioning from soil to leachate;
2. transport of leachate from base of contamination to water table;
3. mixing of leachate and groundwater; and,
4. groundwater transport downgradient to surface water receptor.

Calculations of dilution factors for each of these four processes are shown below.

Dilution Factor 1

Dilution factor 1 is the ratio of the concentration of a contaminant in soil to the concentration in leachate that is in contact with the soil. This dilution factor represents the three phase partitioning between contaminant sorbed to soil, contaminant dissolved in pore water (i.e., as leachate), and contaminant present as soil vapour. It is calculated using the following equation:

$$DF1 = K_{oc} f_{oc} + \frac{(\theta_w + H'\theta_a)}{\rho_b}$$

where,

DF1 = dilution factor 1 ($L \cdot kg^{-1}$);
K_{oc} = organic carbon partition coefficient (81.2 $mL \cdot g^{-1}$; TPHCWG 1997);
f_{oc} = fraction organic carbon (0.005 $g \cdot g^{-1}$; CCME 2000);
θ_w = moisture-filled porosity (0.119 $L \cdot L^{-1}$; CCME 2000);
H' = dimensionless Henry's Law constant (0.225; TPHCWQ 1997);
θ_a = vapour-filled porosity (0.281 $L \cdot L^{-1}$; CCME 2000); and,
ρ_b = dry soil bulk density (1.7 $g \cdot cm^{-3}$; CCME 2000).

Substituting these values in the above equation yields a value for DF1 of 0.51 $L \cdot kg^{-1}$.

Dilution Factor 2

Dilution factor 2 is the ratio of the concentration of a contaminant in leachate that is in contact with the soil, to the concentration in pore water just above the groundwater table. DF2 takes the value 1.00 (i.e., no dilution) for generic guidelines because it is assumed at Tier 1 that the contaminated soil extends down to the water table.

Dilution Factor 3

Dilution factor 3 is the ratio of the concentration of a chemical in pore water just above the groundwater table, to the concentration in groundwater beneath the source. This dilution factor reflects a decrease in concentration as leachate mixes with uncontaminated groundwater. DF3 is a function of groundwater velocity, infiltration rate, source length, and mixing zone thickness. The mixing zone thickness is calculated as being due to two processes: i) mixing due to dispersion, and ii) mixing due to infiltration rate. The equations used are as follows:

$$DF3 = 1 + \frac{Z_d V}{IX}$$

$$Z_d = r + s$$

$$r = 0.01X$$

$$s = d_a \left\{ 1 - \exp\left(\frac{-2.178XI}{Vd_a} \right) \right\}$$

$$V = Ki$$

where,

DF3 = dilution factor 3 (dimensionless);
Z_d = average thickness of mixing zone (0.467 m ; calculated above);
V = Darcy velocity in groundwater (16 m·year^{-1}; calculated above);
I = infiltration (recharge) rate (0.28 m·year^{-1}; CCME 2000);
X = length of contaminated soil (10 m; CCME 2000);
r = mixing depth due to dispersion (0.1 m; calculated above);
s = mixing depth due to infiltration rate (0.367 m; calculated above);
d_a = unconfined aquifer thickness (5 m; CCME 2000);
K = aquifer hydraulic conductivity (320 m·year^{-1}; CCME 2000); and,
i = lateral hydraulic gradient in aquifer (0.05; CCME 2000).

Substituting these values in the above equations yields a DF3 of 3.67 for coarse soil.

Dilution Factor 4

Dilution factor 4 accounts for the processes of dispersion and biodegradation as groundwater travels downgradient from beneath the source of contamination, and is the ratio of the concentration of a chemical in groundwater beneath the source, to the concentration in groundwater at a distance (10 m for Tier 1) downgradient of the source. DF4 was calculated using the following equations:

$$DF4 = \frac{4}{\exp(A) \times erfc(B) \times \left[erf(C) - (D) \right]}$$

$$A = \frac{x}{2D_x} \left\{ 1 - \left(1 + \frac{4L_s D_x}{v} \right)^{1/2} \right\}$$

$$B = \frac{x - vt\left(1 + \frac{4L_s D_x}{v} \right)^{1/2}}{2\left(D_x vt \right)^{1/2}}$$

$$C = \frac{y + \frac{Y}{2}}{2\left(D_y x\right)^{1/2}}$$

$$D = \frac{y - \frac{Y}{2}}{2\left(D_y x\right)^{1/2}}$$

$$L_s = \frac{0.691}{t_{1/2s}} \times \exp\left(-0.07d\right)$$

$$v = \frac{V}{\theta_t R_s}$$

$$R_s = 1 + \frac{\rho_b K_{oc} f_{oc}}{\theta_t}$$

$$D_x = 0.1x$$

$$D_y = 0.01x$$

where,

DF4 = dilution factor 4 (dimensionless);
erf = the error function;
erfc = the complimentary error function;
A = dimensionless group A (-0.038; calculated above);
B = dimensionless group B (-20.4; calculated above);
C = dimensionless group C (7.50; calculated above);
D = dimensionless group D (-7.50; calculated above);
x = distance to receptor (10 m; CCME 2000);
D_x = dispersivity in the direction of groundwater flow (1.0 m; calculated above);
L_s = decay constant (0.56 year^{-1}; calculated above);
v = velocity of the contaminant (14.65 m· year^{-1}; calculated above);
t = time since the contaminant release (100 years; CCME 2000);
y = distance to receptor perpendicular to groundwater flow (0 m; CCME 2000);
Y = source width (30 m; CCME 2000);
D_y = dispersivity perpendicular to the direction of groundwater flow (0.10 m; calculated above);
$t_{1/2s}$ = decay half-life of chemical in saturated zone (1 year; BCMELP 1996);
d = depth to groundwater (3 m; CCME 2000);

V = Darcy velocity in groundwater (16 m·year^{-1}; calculated above);
θ_t = total soil porosity (0.40; CCME 2000);
R_s = retardation factor in saturated zone (2.73; calculated above);
ρ_b = dry soil bulk density (1.7 g·cm^{-3}; CCME 2000);
K_{oc} = organic carbon partition coefficient (81.2 mL·g^{-1};TPHCWG 1997); and,
f_{oc} = fraction organic carbon (0.005 g·g^{-1}; CCME 2000).

Substituting these values into the above equations yields a value for DF4 of 1.445 for benzene in coarse soil.

Check value

The groundwater check for the protection of aquatic life was calculated using the following equations:

$$GWC_{AL} = WQG_{AL} \times DF$$

$$DF = DF1 \times DF2 \times DF3 \times DF4$$

where,

GWC_{AL} = groundwater check protective of aquatic life (mg·kg^{-1});
WQG_{AL} = water quality guideline for aquatic life (0.37 mg·L^{-1});
DF = overall dilution factor (2.7 L·kg^{-1});
DF1 = dilution factor 1 (0.51 L·kg^{-1});
DF2 = dilution factor 2 (1.00);
DF3 = dilution factor 3 (3.67); and,
DF4 = dilution factor 4 (1.44).

Substituting these values in the above equations and rounding to 2 significant figures yields a groundwater check for the protection of aquatic life for benzene in coarse soil of 1.0 mg·kg^{-1}.

Protection of Groundwater for Livestock Watering

This check value was calculated to determine the concentration of benzene in soil that will not cause groundwater concentrations to exceed acceptable levels for consumption by livestock. This pathway applies only to agricultural land uses. As with the aquatic life groundwater check, the livestock watering groundwater check is the same for both surface soils and subsoils, and is calculated only for coarse soils (not fine). The calculations for the groundwater check for the protection of livestock watering are identical to those shown above for the groundwater check for aquatic life, except that a livestock watering threshold limit is used (TL_{LW}), rather than the WQG_{AL}. This check value is provisional because at the time of derivation there was no Canadian Water Quality Guideline for the protection of livestock watering on which to base it (CCME 1999). Instead, using parameters for dairy cows, a health-based livestock watering threshold limit was calculated using the following equation:

$$TL_{LW} = \left(\frac{BW \times DTED}{IR_W \times BIO_O} \right)$$

where,

TL_{LW} = water quality threshold limit for livestock watering ($mg \cdot L^{-1}$);
BW = body weight for cattle (701 kg; CCME 1999);
DTED = daily threshold effect dose for benzene (0.08 $mg \cdot kg^{-1}$ $bw \cdot d^{-1}$; calculated above for the soil and food ingestion guideline);
IR_W = drinking water ingestion rate for cattle (87.5 $L \cdot d^{-1}$; CCME 1999); and,
BIO_O = oral bioavailability (gut absorption factor) (1.0; assumed).

Substituting these values into the above equation and rounding to 2 significant figures yields a livestock watering threshold limit for benzene of 0.64 $mg \cdot L^{-1}$.

Check value

The groundwater check for the protection of livestock watering was calculated using the following equations:

$$GWC_{LW} = TL_{LW} \times DF$$

$$DF = DF1 \times DF2 \times DF3 \times DF4$$

where,

GWC_{LW} = groundwater check protective of livestock watering ($mg \cdot kg^{-1}$);
TL_{LW} = threshold limit for livestock watering (0.64 $mg \cdot L^{-1}$; calculated above);
DF = overall dilution factor (2.7 $L \cdot kg^{-1}$; calculated above);
DF1 = dilution factor 1 (0.51 $L \cdot kg^{-1}$; calculated for GWC_{AL});
DF2 = dilution factor 2 (1.00; calculated for GWC_{AL});
DF3 = dilution factor 3 (3.67; calculated for GWC_{AL}); and,
DF4 = dilution factor 4 (1.44; calculated for GWC_{AL}).

Substituting these values into the above equations and rounding to 2 significant figures yields a groundwater check for the protection of livestock watering for benzene in coarse soil of 1.7 $mg \cdot kg^{-1}$.

CHAPTER 7. DERIVATION OF HUMAN HEALTH SOIL QUALITY GUIDELINES

The derivation of human health soil quality guidelines for benzene is outlined in the following sections for four land uses: agricultural, residential/parkland, commercial, and industrial. Various modifications to the CCME (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. Modifications include 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. These human health soil quality guidelines for benzene will be considered along with the environmental guidelines in making final recommendations for Canadian Soil Quality Guidelines for the protection of environmental and human health (CCME 1996; see Chapter 8).

The overall human health soil quality guidelines (SQG_{HH}) were determined by considering four exposure pathways: soil ingestion, soil dermal contact, indoor vapour inhalation, and ingestion of contaminated groundwater.

Human Exposure Limits

Benzene has been classified as a human carcinogen by Health Canada (1996a). Thus, it is considered as a nonthreshold toxicant (a substance for which there is considered to be some probability of harm from the critical effect at any level of exposure) requiring the development of soil quality guidelines that are based on lifetime incremental risks from exposure. For all land uses, the adult was chosen as the receptor when considering lifetime cancer risk (CCME 1996). The selection of acceptable levels of risk is a policy decision. The CCME Subcommittee on Environmental Quality Criteria for Contaminated Sites recommended the development of soil guidelines based on an incremental cancer risk from soil exposure within the range of 10^{-4} to 10^{-7} (CCME 1996). Most Canadian jurisdictions have settled on either 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, guideline values for non-drinking water pathways are provided 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 Guidelines for Canadian Drinking Water Quality are employed, when available, as acceptable 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. As a result, no range in acceptable risk limits 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 of Maximum Acceptable Concentrations (MACs) for carcinogenic chemicals in drinking water (Health and Welfare Canada 1989).

For carcinogens, inhalation exposure is assessed relative to a risk-specific concentration (RsC), while ingestion exposure is assessed relative to a risk-specific dose (RsD). Health Canada (1996a) provides an inhalation tolerable concentration at a 5% cancer risk for lifetime exposure of 15 $mg \cdot m^{-3}$. The risk-specific concentration (RsC) for inhalation evaluated at excess cancer risks of 10^{-6} (i.e., 1 in 1,000,000) and 10^{-5} (i.e., 1 in 100,000) were calculated by multiplying this value by $10^{-6}/0.05$ or $10^{-5}/0.05$ to give values of 0.0003 and 0.003 $mg \cdot m^{-3}$, respectively. For ingestion, Health Canada (2003) provides an oral slope factor for benzene of 0.31 $(mg \cdot kg^{-1}\ bw \cdot d^{-1})^{-1}$. The risk-specific dose (RsD) was calculated by dividing the level of risk (i.e., 10^{-6} or 10^{-5}) by the slope factor to give values of 3.2×10^{-6} and 3.2×10^{-5} $mg \cdot kg^{-1}\ bw \cdot d^{-1}$, respectively. The risk-specific dose for ingestion is also applied to dermal exposure.

The RsD and RsC values for various lifetime incremental cancer risk levels are given in the table below:

Lifetime incremental risk	Concentration ($mg \cdot m^{-3}$)	Dose ($mg \cdot kg^{-1}\ bw \cdot d^{-1}$)
10^{-4}	0.03	0.00032
10^{-5}	0.003	0.000032
10^{-6}	0.0003	0.0000032
10^{-7}	0.00003	0.00000032

Background Exposure

The possibility of receptors being exposed to levels of benzene contamination in background soils was considered, and included in the equations used to calculate guidelines for human exposure pathways. However, as natural sources of benzene are relatively small, the background level of benzene in soil was assumed to be zero.

Soil Ingestion

The guidelines for this pathway are the same for coarse and fine soil and for all four land uses. No subsoil quality guidelines are calculated for this pathway, based on the lack of direct contact to subsoils for most receptors. The SQG_{SI} for benzene in surface soils was calculated using the following equation:

$$SQG_{SI} = \frac{RsD \times BW \times 10^3}{SIR \times AF_G \times ET}$$

where,

SQG_{SI} = human health soil quality guideline for soil ingestion (mg·kg^{-1});
RsD = risk-specific dose evaluated at an excess cancer risk of 1 in 1,000,000 (3.2 x 10^{-6} mg·kg^{-1} bw·d^{-1}; see above) or 1 in 100,000 (3.2 x 10^{-5} mg·kg^{-1} bw·d^{-1}; see above);
BW = adult body weight (70.7 kg; CCME 2000);
10^3 = conversion factor from kg to g;
SIR = soil ingestion rate for the adult (0.02 g·d^{-1}; CCME 2000);
AF_G = absorption factor for gut (1; assumed); and,
ET = exposure term (1; represents a fully exposed individual).

Substituting these values into the above equation and rounding to 2 significant figures yields values of 11 mg·kg^{-1} (for an incremental cancer risk of 10^{-6}) or 110 mg·kg^{-1} (for an incremental cancer risk of 10^{-5}), as the guideline for incidental human soil ingestion of benzene for all land uses and soil textures.

Soil Dermal Contact

The guidelines for this pathway are the same for coarse and fine soil. No subsoil quality guidelines are calculated for this pathway based on the lack of direct contact to subsoils for most receptors. The SQG_{DC} for benzene in surface soils was calculated using the following equation:

$$SQG_{DC} = \frac{RsD \times BW \times 10^6}{AF_D \times \{(SA_{hand} \times DL_{hands}) + (SA_{other} \times DL_{other})\} \times EF \times ET}$$

where,

SQG_{DC} = human health soil quality guideline for soil dermal contact (mg·kg^{-1});
RsD = risk-specific dose evaluated at an excess cancer risk of 1 in 1,000,000 (3.2 x 10^{-6} mg·kg^{-1} bw·d^{-1}; see above) or 1 in 100,000 (3.2 x 10^{-5} mg·kg^{-1} bw·d^{-1}; see above);
BW = adult body weight (70.7 kg; CCME 2000);
10^6 = conversion factor from kg to mg;
AF_D = absorption factor for soil dermal contact (0.08; CCME 2000);
SA_{hands} = adult surface area of hands (890 cm^2; CCME 2000);
DL_{hands} = dermal soil loading for an adult's hands (0.1 mg·cm^{-2}·event^{-1}; CCME 2000);
SA_{other} = adult surface area for other exposed skin (2500 cm^2; CCME 2000);

DL_{other} = adult dermal soil loading for other exposed skin (0.01 mg·cm^{-2}·event^{-1}; CCME 2000);
EF = exposure frequency (1 event·day^{-1}); and,
ET = exposure term (1; represents a fully exposed individual).

Substituting these values into the above equation and rounding to 2 significant figures yields a value of 25 mg·kg^{-1} (for an incremental cancer risk of 10^{-6}) or 250 mg·kg^{-1} (for an incremental cancer risk of 10^{-5}) as the guideline for human soil dermal contact for benzene for all land uses and soil textures.

Indoor Vapour Inhalation

The guidelines for this pathway are different for coarse and fine soil, and also for surface soil and subsoil. In addition, for the agricultural and residential land uses, different guidelines are calculated depending on whether the building has a basement, or is of slab-on-grade construction. For completeness, the soil quality guidelines for the indoor vapour inhalation pathway (SQG_{II}) for both construction types are calculated here; however, in all cases the slab-on-grade is the lower of the two. The SQG_{II} values for benzene are calculated using the following equations, and the appropriate parameter values from Table 1.

$$SQG_{II} = \frac{RsC \times \left[\theta_w + \left(K_{oc} \times f_{oc} \times \rho_b\right) + \left(H' \times \theta_a\right)\right] \times DF_i \times 10^3}{H' \times \rho_b \times ET \times 10^6}$$

where,

SQG_{II} = soil quality guideline for indoor infiltration (mg·kg^{-1});
RsC = risk-specific concentration;
θ_w = moisture-filled porosity;
K_{oc} = organic carbon partition coefficient;
f_{oc} = fraction organic carbon;
ρ_b = dry soil bulk density;
H' = dimensionless Henry's Law Constant;
θ_a = vapour-filled porosity;
DF_i = dilution factor from soil gas to indoor air;
10^3 = conversion factor from kg to g;
ET = exposure term; and,
10^6 = conversion factor from m^3 to cm^3.

Table 1. Parameter values used for calculating indoor vapour inhalation guidelines.

Parameter (units)	Basement				Slab-on-grade			
	Surface soil		Subsoil		Surface soil		Subsoil	
	coarse	fine	coarse	fine	coarse	fine	coarse	fine
RsC ($mg \cdot m^{-3}$)[a]								
10^{-6} incremental risk	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003
10^{-5} incremental risk	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
θ_w ($L \cdot L^{-1}$)[b]	0.119	0.168	0.119	0.168	0.119	0.168	0.119	0.168
K_{oc} ($mL \cdot g^{-1}$)[c]	81.2	81.2	81.2	81.2	81.2	81.2	81.2	81.2
f_{oc} ($g \cdot g^{-1}$)[b]	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
ρ_b ($g \cdot cm^{-3}$)[b]	1.7	1.4	1.7	1.4	1.7	1.4	1.7	1.4
H' (unitless)[c]	0.225	0.225	0.225	0.225	0.225	0.225	0.225	0.225
θ_a ($L \cdot L^{-1}$)[b]	0.281	0.132	0.281	0.132	0.281	0.132	0.281	0.132
DF_I (unitless)[d]								
Agr/Res/Park	22482	301296	23507	308356	13914	302663	14735	315024
Comm/Ind	N/A	N/A	N/A	N/A	44248	384763	46684	400160
ET (unitless)[b]	1	1	1	1	1	1	1	1

N/A = not applicable

[a] See above

[b] CCME 2000

[c] TPHCWG 1997

[d] See derivation below

Assuming an incremental cancer risk of 10^{-6}, substituting these values in the above equation and rounding to 2 significant figures yields values for agricultural and residential/parkland land uses with basement construction of 0.015 $mg \cdot kg^{-1}$ (coarse surface soil), 0.21 $mg \cdot kg^{-1}$ (fine surface soil), 0.015 $mg \cdot kg^{-1}$ (coarse subsoil), and 0.21 $mg \cdot kg^{-1}$ (fine subsoil). Values for agricultural and residential/parkland land uses with slab-on-grade construction are 0.0095 $mg \cdot kg^{-1}$ (coarse surface soil), 0.21 $mg \cdot kg^{-1}$ (fine surface soil), 0.011 $mg \cdot kg^{-1}$ (coarse subsoil), and 0.22 $mg \cdot kg^{-1}$ (fine subsoil). Values for commercial and industrial land uses with slab-on-grade construction are 0.030 $mg \cdot kg^{-1}$ (coarse surface soil), 0.28 $mg \cdot kg^{-1}$ (fine surface soil), 0.032 $mg \cdot kg^{-1}$ (coarse subsoil), and 0.29 $mg \cdot kg^{-1}$ (fine subsoil). These are the guidelines for indoor vapour inhalation of benzene.

The indoor vapour inhalation guidelines for an incremental cancer risk of 10^{-5} can be determined by taking the corresponding guideline value at an incremental risk of 10^{-6} and multiplying by a factor of 10.

Dilution Factor

The dilution factor (DF_i) was calculated as follows:

$$DF_i = \frac{1}{\alpha}$$

where,

DF_i = dilution factor from soil gas concentration to indoor air concentration (unitless); and,

α = attenuation coefficient (unitless; see derivation below).

Calculation of α for Coarse Soils

The attenuation coefficients for coarse soils were calculated using the following equations:

$$\alpha = \frac{\left(\dfrac{D_T^{eff} \times A_B}{Q_B \times L_T}\right)}{\left(\dfrac{D_T^{eff} \times A_B}{Q_{soil} \times L_T}\right) + 1}$$

$$D_T^{eff} = D_a \times \left(\frac{\theta_a^{10/3}}{\theta_t^2}\right)$$

$$A_B = (L_B W_B) + 2Z_{crack} \times (L_B + W_B)$$

$$Q_B = \frac{L_B W_B H_B ACH}{3600}$$

$$Q_{soil} = \frac{2\pi \Delta P k_v X_{crack}}{\mu \ln\left[\dfrac{2Z_{crack}}{r_{crack}}\right]}$$

where,

α = attenuation coefficient (unitless);

D_T^{eff} = effective porous media diffusion coefficient based on vapour-phase concentrations for the region between the source and foundation (0.00799 $cm^2 \cdot s^{-1}$; calculated using equation above);

A_B = below ground building area (2,700,000 cm^2 for agricultural and residential basements; 1,560,000 cm^2 for agricultural and residential slab-on-grade; 3,080,000 cm^2 for commercial and industrial slab-on-grade; calculated using equation above);

Q_B = building ventilation rate (203,000 $cm^3 \cdot s^{-1}$ for agricultural and residential land uses; 500,000 $cm^3 \cdot s^{-1}$ for commercial and industrial land uses; calculated using equation above);

L_T = distance from contaminant source to foundation (30 cm for surface soil; 139 cm for subsoil; CCME 2000);

Q_{soil} = volumetric flow rate of soil gas into the building (9.144 $cm^3 \cdot s^{-1}$ for agricultural and residential basements; 15.12 $cm^3 \cdot s^{-1}$ for agricultural and residential slab-on-grade; 11.4 $cm^3 \cdot s^{-1}$ for commercial and industrial slab-on-grade; calculated using equation above);

D_a = diffusion coefficient in air (0.088 $cm^2 \cdot s^{-1}$; TPHCWG 1997);

θ_a = soil vapour-filled porosity (0.281 $L \cdot L^{-1}$; CCME 2000);

θ_t = soil total porosity (0.4 $L \cdot L^{-1}$; CCME 2000);

L_B = building length (1225 cm for agricultural and residential land uses; 2000 cm for commercial and industrial land uses; CCME 2000);

W_B = building width (1225 cm for agricultural and residential land uses; 1500 cm for commercial and industrial land uses; CCME 2000);

H_B = building height (488 cm for agricultural and residential land uses; 300 cm for commercial and industrial land uses; CCME 2000);

ACH = air exchanges per hour (1 $exch \cdot h^{-1}$ for agricultural and residential land uses; 2 $exch \cdot h^{-1}$ for commercial and industrial land uses; CCME 2000);

3600 = conversion factor from hours to seconds

ΔP = pressure differential (40 $g \cdot cm^{-2}$ for agricultural and residential land uses; 20 $g \cdot cm^{-2}$ for commercial and industrial land uses; CCME 2000);

k_v = soil vapour permeability to vapour flow (10^{-8} for coarse soil; 10^{-9} for fine soil; CCME 2000);

X_{crack} = length of idealized cylinder (4900 cm for agricultural and residential land uses; 7000 cm for commercial and industrial land uses; CCME 2000);

μ = vapour viscosity (1.73×10^{-4} $g \cdot cm^{-1} \cdot s^{-1}$; CCME 2000);

Z_{crack} = distance below grade to idealized cylinder (244 cm for basement; 11.25 cm for slab-on-grade; CCME 2000); and,

r_{crack} = radius of idealized cylinder (0.203 cm for agricultural and residential land uses; 0.264 cm for commercial and industrial land uses; CCME 2000).

Substituting these values in the above equations yields values for α in coarse surface soils on agricultural and residential lands of 4.448×10^{-5} for basements and 7.187×10^{-5} for slab-on-grade construction. In coarse subsoils on agricultural and residential lands, α is 4.254×10^{-5} for basements and 6.787×10^{-5} for slab-on-grade construction. In coarse soils on commercial and industrial lands, α is 2.26×10^{-5} for surface soil and 2.142×10^{-5} for subsoil.

Calculation of α for Fine Soils

The attenuation coefficients for fine soils were calculated using the following equations:

$$\alpha = \frac{\left(\dfrac{D_T^{eff} \times A_B}{Q_B \times L_T}\right)}{1 + \left(\dfrac{D_T^{eff} \times A_B}{Q_B \times L_T}\right) + \left(\dfrac{D_T^{eff} \times A_B \times L_{crack}}{D_{crack} \times A_{crack} \times L_T}\right)}$$

$$D_T^{eff} = D_a \times \left(\frac{\theta_a^{10/3}}{\theta_t^2}\right)$$

where,

α = attenuation coefficient (unitless);

D_T^{eff} = effective porous media diffusion coefficient based on vapour-phase concentrations for the region between the source and foundation (0.00115 $cm^2 \cdot s^{-1}$; calculated using equation above);

A_B = below ground building area (2,700,000 cm^2 for agricultural and residential basements; 1,560,000 cm^2 for agricultural and residential slab-on-grade; 3,080,000 cm^2 for commercial and industrial slab-on-grade; see derivation above for coarse soil);

Q_B = building ventilation rate (203,000 $cm^3 \cdot s^{-1}$ for agricultural and residential land uses; 500,000 $cm^3 \cdot s^{-1}$ for commercial and industrial land uses; see derivation above for coarse soil);

L_T = distance from contaminant source to foundation (30 cm for surface soil; 139 cm for subsoil; CCME 2000);

L_{crack} = thickness of the foundation (11.25 cm; CCME 2000);

D_{crack} = effective diffusion coefficient through the crack; it is assumed that the cracks are filled with coarse soil, and accordingly D_{crack} is D_T^{eff} for coarse soils (0.00799 $cm^2 \cdot s^{-1}$; see above);

A_{crack} = area of cracks through which contaminant vapours enter building (955 cm^2 for agricultural and residential land use; 1850 cm^2 for commercial and industrial land use; CCME 2000);

D_a = diffusion coefficient in air (0.088 $cm^2 \cdot s^{-1}$; TPHCWG 1997);

θ_a = soil vapour-filled porosity (0.132 $L \cdot L^{-1}$; CCME 2000); and,

θ_t = soil total porosity (0.3 $L \cdot L^{-1}$; CCME 2000).

Substituting these values into the above equations yields values for α in fine surface soils on agricultural and residential lands of 3.319×10^{-6} for basements and 3.304×10^{-6} for slab-on-grade construction. In fine subsoils on agricultural and residential lands, α is 3.243×10^{-6} for basements and 3.174×10^{-6} for slab-on-grade construction. In fine soils on commercial and industrial lands, α is 2.599×10^{-6} for surface soil and 2.499×10^{-6} for subsoil.

Protection of Potable Groundwater

The groundwater check values for the protection of potable (drinking) water for benzene are calculated using the formula from the PHC CWS, adapted to use the Guidelines for Canadian Drinking Water Quality (Health Canada 1996b) as the toxicological basis, rather than the TDI. Groundwater check values are calculated separately for coarse and fine soils, but for soils of the same texture, the check values do not differ between surface and subsoil nor across different land uses. The check values are calculated using the following equations:

$$GWC_P = WQG_{DW} \times \left[K_d + \left(\frac{\theta_m}{\rho_w} \right) \right] \times DF_w$$

$$K_d = K_{oc} \times f_{oc}$$

$$DF_w = \frac{B \times K \times i}{I \times L} + 1$$

where,

GWC_P = groundwater check for the protection of potable water (mg·kg^{-1});
WQG_{DW} = drinking water quality guideline (0.005 mg·L^{-1}; Health Canada 1996b);
K_d = chemical-specific distribution coefficient (0.406 mL·g^{-1}; calculated above);
K_{oc} = organic carbon partition coefficient (81.2 mL·g^{-1};TPHCWG 1997);
f_{oc} = fraction organic carbon (0.005 g·g^{-1}; CCME 2000);
θ_m = soil water content (0.07 g·g^{-1} coarse soil; 0.12 g·g^{-1} fine soil; CCME 2000);
ρ_w = density of water (1.0 g·cm^{-3}; CCME 2000);
DF_w = groundwater/pore water dilution factor (unitless) (12.4 for coarse soil; 2.6 for fine soil; calculated above);
B = effective mixing depth in aquifer (2 m; CCME 2000);
K = saturated hydraulic conductivity of aquifer (320 m·year^{-1} coarse soil; 32 m·year^{-1} fine soil; CCME 2000);
i = hydraulic gradient (0.05; CCME 2000);
I = infiltration (recharge) rate (0.28 m·year^{-1} coarse soil; 0.20 m·year^{-1} fine soil; CCME 2000); and,
L = site length (10 m; CCME 2000).

Substituting these values into the above equations and rounding to 2 significant figures yields values of 0.030 mg·kg^{-1} for coarse soil and 0.0068 mg·kg^{-1} for fine soil, which are the groundwater check values for the protection of potable (drinking) groundwater for benzene.

Final Human Health Soil Quality Guidelines

The final human health soil quality guidelines (SQG_{HH}) for benzene for the two soil textures and two soil depths in each of the four land uses are presented in Tables 2 and 3.

Agricultural Land Use

The SQG_{HH} is based on the most sensitive of the various guidelines and check values calculated for human health. With a 10^{-6} incremental risk, for coarse soils on agricultural lands, the most sensitive pathway is the inhalation of indoor air check for slab-on-grade construction; therefore, the SQG_{HH} values for coarse surface soils and subsoils are 0.0095 and 0.011 $mg \cdot kg^{-1}$, respectively. In the case of a 10^{-5} incremental risk, for coarse soils on agricultural lands, the most sensitive pathway is the groundwater check for the protection of drinking water; therefore, the SQG_{HH} value for both coarse surface soils and subsoils is 0.030 $mg \cdot kg^{-1}$. For fine soils, the most sensitive pathway for incremental risks of 10^{-5} and 10^{-6} is the groundwater check for the protection of drinking water; therefore at both incremental risk levels the SQG_{HH} for both fine surface soils and subsoils is 0.0068 $mg \cdot kg^{-1}$.

Residential/Parkland Land Use

The SQG_{HH} is based on the most sensitive of the various guidelines and check values calculated for human health. With a 10^{-6} incremental risk, for coarse soils on residential/parkland lands, the most sensitive pathway is the inhalation of indoor air check for slab-on-grade construction; therefore, the SQG_{HH} values for coarse surface soils and subsoils are 0.0095 and 0.011 $mg \cdot kg^{-1}$, respectively. In the case of a 10^{-5} incremental risk, for coarse soils on residential/parkland lands, the most sensitive pathway is the groundwater check for the protection of drinking water; therefore, the SQG_{HH} value for both coarse surface soils and subsoils is 0.030 $mg \cdot kg^{-1}$. For fine soils, the most sensitive pathway for incremental risks of 10^{-5} and 10^{-6} is the groundwater check for the protection of drinking water; therefore at both incremental risk levels the SQG_{HH} for both fine surface soils and subsoils is 0.0068 $mg \cdot kg^{-1}$.

Commercial Land Use

The SQG_{HH} is based on the most sensitive of the various guidelines and check values calculated for human health. For both coarse and fine soils on commercial lands, and at both incremental risk levels, the most sensitive pathway is the groundwater check for the protection of drinking water. Therefore, the SQG_{HH} value for both coarse surface soils and subsoils is 0.030 $mg \cdot kg^{-1}$ and the SQG_{HH} value for both fine surface soils and subsoils is 0.0068 $mg \cdot kg^{-1}$.

Industrial Land Use

The SQG_{HH} is based on the most sensitive of the various guidelines and check values calculated for human health. For both coarse and fine soils on industrial lands, and at both incremental risk levels, the most sensitive pathway is the groundwater check for the protection of drinking water. Therefore, the SQG_{HH} value for both coarse surface soils and subsoils is 0.030 mg·kg^{-1} and the SQG$_{HH}$ value for both fine surface soils and subsoils is 0.0068 mg·kg^{-1}.

CHAPTER 8. RECOMMENDED CANADIAN SOIL QUALITY GUIDELINES

According to the formal protocol (CCME 1996), both environmental and human health soil quality guidelines are developed for four land uses: agricultural, residential/parkland, commercial, and industrial. The lowest value generated by the two approaches for each of the four land uses is recommended by the CCME as the Canadian Soil Quality Guideline. The environmental soil quality guidelines for benzene, presented in Chapter 6, were considered along with the human health guidelines, presented in Chapter 7 in making final recommendations for Canadian Soil Quality Guidelines for the protection of environmental and human health. The recommended Canadian Soil Quality Guidelines for the protection of environmental and human health (CCME 1999) are presented below in Tables 2 and 3. The interim remediation criteria (CCME 1991) are also presented for comparison purposes.

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

	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; 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 1996). 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 Chapter 6. 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 $m \cdot y^{-1}$ 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.

	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^{-6} 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[ii]	1.0[j]	NC[i]
Interim soil quality criterion (CCME 1991)	0.05		0.5		5		5	

Notes: NC = not calculated; 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 1996). 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 Chapter 6. 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 $m \cdot y^{-1}$ 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.

CHAPTER 9. AREAS FOR FUTURE RESEARCH

The guidelines developed in this document are based on the best available data. In the process of deriving these guidelines, however, it was noted that there are certain areas of study in which limited data are available for benzene. This chapter highlights some of the gaps in our knowledge for this substance with the hope that it will provide stimulation and direction for further research.

The soil quality guidelines for environmental health recommended in this document are based on limited toxicity data for soil invertebrates and terrestrial plants. Studies on additional species would be useful, particularly other invertebrates as they appear to be more sensitive to benzene than plants. Our understanding of benzene toxicity would also benefit particularly from studies examining chronic effects in plants and chronic non-lethal effects (such as reductions in growth or reproduction) in invertebrates.

There is a lack of studies on the toxic effects of benzene on livestock, mammalian wildlife, and birds. Also needed are studies on the metabolism of benzene in mammals and birds, as well as invertebrates.

A nutrient and energy cycling check could not be calculated for benzene due to a lack of data on microbial processes. Research is needed into the effects of benzene on nitrogen fixation, nitrification, nitrogen mineralization, decomposition, and respiration.

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APPENDIX I. PHYSICAL AND CHEMICAL PROPERTIES OF BENZENE

Property	Value
Melting point	5.53°C
Boiling point	80.1°C (at 101.3 kPa)
Flash point	-11°C
Specific gravity	0.88 (liquid density)
Solubility	0.18 g·100 mL^{-1} (at 25°C)
Vapour pressure	13.33 kPa or 100 mm Hg (at 26°C)
Autoignition temperature	562°C
Vapour density	4.0 (at 90°C; air =1)
Log K_{ow}	2.13 (at 20°C)
Henry's Law Constant	0.55 kPa·m^{-3}·mol^{-1}

Source: Mackay et al. (1992)

APPENDIX II. EXISTING GUIDELINES/CRITERIA FROM VARIOUS JURISDICTIONS FOR BENZENE IN SOIL

Jurisdiction	Category	Guideline /criteria ($mg\cdot kg^{-1}$)	Reference
Canada	Interim remediation criteria		CCME 1991
	Agricultural	0.05	
	Residential/Parkland	0.5	
	Commercial/Industrial	5	
Ontario	Surface soil clean-up criteria in a potable groundwater situation (soil pH 5–9)		OMEE 1994
	Agricultural	0.05	
	Residential/Parkland	0.05	
	Commercial/Industrial	0.05	
	Surface soil clean-up criteria in a non-potable groundwater situation (soil pH 5–9)		
	Residential/Parkland	0.05	
	Commercial/Industrial	0.5	
	Sub-surface soil clean-up criteria in a potable groundwater situation (soil pH 5–11)		
	Residential/Parkland	0.05	
	Industrial/Commercial	0.05	
	Sub-surface soil clean-up criteria in a non-potable groundwater situation (soil pH 5–11)		
	Residential/Parkland	0.5	
	Industrial/Commercial	2	
	Groundwater for all land uses		
	Potable groundwater	5 $\mu g\cdot L^{-1}$	
	Non-Potable groundwater	1900 $\mu g\cdot L^{-1}$	
Alberta	Tier 1 criteria	0.05	Angus Environmental Ltd 1991
British Columbia	Reference value	0.1	Angus Environmental Ltd 1991
	Residential/Recreational/Agricultural	0.5	
	Commercial/Industrial	5	
California	Maximum concentration for soil		California State Leaking Underground Storage Fuel Tank Task Force 1988
	with low leaching potential	1	
	with medium leaching potential	0.3	
New Hampshire	Soil clean-up guideline for virgin petroleum contaminates soils	0.2	New Hampshire Department of Environmental Services 1994
Tennessee	Residential	0.5	Sittig 1994

Jurisdiction	**Category**	**Guideline /criteria ($mg\cdot kg^{-1}$)**	**Reference**
	Industrial	0.5	
Oregon	Residential	1	Sittig 1994
	Industrial	2	
Texas	Residential	1.33	Sittig 1994
	Industrial	1.62	
Arizona	Residential	47	Sittig 1994
New York		24	
Washington		34.5	
The Netherlands	Soil target value	0.05	RIVM 1994
	Soil requires intervention	1	
	Groundwater target value	0.2 $\mu g\cdot L^{-1}$	
	Groundwater intervention value	30 $\mu g\cdot L^{-1}$	

APPENDIX III. CONSULTED TOXICOLOGICAL STUDIES ON THE EFFECTS OF BENZENE ON TERRESTRIAL ORGANISMS

Organism	Effect	Endpoint†	Effect Concentration ($mg \cdot kg^{-1}$)	Test Substrate (Exposure period)	Reference
Radish *Raphanus sativus*	seedling emergence	NOEC	548 applied 16 recovered	50% artificial soil 50% sand 80% moisture	Environment Canada 1995
	70% reduction in seedling emergence	LOEC	1096 applied 32 recovered	(3 d)	
	reduction in seedling emergence	EC$_{25}$	783 applied 22 recovered		
	reduction in seedling emergence	EC$_{50}$	961 applied 27 recovered		
Radish *Raphanus sativus*	root length	NOEC	274 applied 8 recovered	artificial soil topped with filter; filter hydrated with 2 mL DRO; 100% moisture	Environment Canada 1995
	23% reduction in root length	LOEC	548 applied 16 recovered		
	reduction in root length	EC$_{25}$	467 applied 14 recovered	(3d)	
	reduction in root length	EC$_{50}$	1333 applied 39 recovered		
Radish *Raphanus sativus*	seedling emergence	NOEC	137 applied 15 recovered	60% artificial soil 40% sand 80% moisture	Environment Canada 1995
	33% reduction in seedling emergence	LOEC	274 applied 29 recovered	(3 d)	
	reduction in seedling emergence	EC$_{25}$	240 applied 26 recovered		
	reduction in seedling emergence	EC$_{50}$	959 applied 102 recovered		

Organism	Effect	Endpoint†	Effect Concentration (mg·kg^{-1})	Test Substrate (Exposure period)	Reference
Lettuce *Lactuca sativa*	root length	NOEC	1096 applied 32 recovered	artificial soil topped with filter hydrated with 2 mL DRO 100% moisture (5 d)	Environment Canada 1995
	77% reduction in root length	LOEC	2191 applied 64 recovered		
	reduction in root length	EC_{25}	1031 applied 30 recovered		
	reduction in root length	EC_{50}	1562 applied 46 recovered		
Lettuce *Lactuca sativa*	seedling emergence	NOEC	137 applied 4 recovered	50% artificial soil 50% sand 80% moisture (5 d)	Environment Canada 1995
	33% reduction in seedling emergence	LOEC	274 applied 8 recovered		
	reduction in seedling emergence	EC_{25}	240 applied 7 recovered		
	reduction in seedling emergence	EC_{50}	890 applied 26 recovered		
Lettuce *Lactuca sativa*	seedling emergence	NOEC	548 applied 58 recovered	60% artificial soil 40% sand 80% moisture (5 d)	Environment Canada 1995
	67% reduction in seedling emergence	LOEC	1096 applied 117 recovered		
	reduction in seedling emergence	EC_{25}	685 applied 73 recovered		
	reduction in seedling emergence	EC_{50}	932 applied 99 recovered		

Organism	Effect	Endpoint†	Effect Concentration ($mg\cdot kg^{-1}$)	Test Substrate (Exposure period)	Reference
Lettuce *Lactuca sativa*	Root length	NOEC	274 applied 29 recovered	artificial soil topped with filter; filter hydrated with 2 mL DRO; 100% moisture (5 d)	Environment Canada 1995
	54% reduction in root length	LOEC	1096 applied 117 recovered		
	reduction in root length	EC_{25}	527 applied 56 recovered		
	reduction in root length	EC_{50}	970 applied 103 recovered		
Earthworm *Eisenia foetida*	survival	LC_{50}	98 $\mu g\cdot cm^{-2}$	filter paper (2 d)	Newhauser et al. 1986
Earthworm *Eisenia foetida*	survival	LC_{50}	100-1000 $\mu g\cdot cm^{-2}$	filter paper (2 d)	Roberts and Dorough 1984
Earthworm *Eisenia foetida*	growth	NOEC	4% (w/w) dissolved in 30g sludge with 13% solids	4 mm layer of silt loam in petri dish (6 wks)	Hartenstein 1982
	growth	LOEC	8% (w/w) same as above		
Mosquito *Aedes aegypti*	survival	LC_{50}	59.3 $mg\cdot L^{-1}$	glass bowls of distilled water (24 h)	Berry and Brammer 1977
		non-lethal dose	12.9 $mg\cdot L^{-1}$		
Nematode *Panagrellus redivivus*	survival	NOEC	7.8 $mg\cdot L^{-1}$	methanol extract of artificial soil 70% industrial sand 20% clay 10% sphagnum peat moss (4 d)	Samoiloff et al. 1980
	growth	NOEC	7.8 $mg\cdot L^{-1}$		
	maturation	NOEC	0.78 $mg\cdot L^{-1}$		

Organism	Effect	Endpoint†	Effect Concentration ($mg\cdot kg^{-1}$)	Test Substrate (Exposure period)	Reference
Earthworm *Eisenia foetida*	mortality	NOEC	2191 applied 234 recovered	artificial soil 80% moisture	Environment Canada 1995
	100% mortality	LOEC	4383 applied 467 recovered	(7 d)	
		LC_{25}	2622 applied 280 recovered		
		LC_{50}	3209 applied 342 recovered		
Earthworm *Eisenia foetida*	mortality	NOEC	1096 applied 32 recovered	artificial soil 80% moisture	Environment Canada 1995
	60% mortality	LOEC	2191 applied 64 recovered	(7 d)	
		LC_{25}	1440 applied 42 recovered		
		LC_{50}	1880 applied 55 recovered		
Soil mycobacterium *Mycobacterium vaccae*	Cell viability (colony forming units)	No effect	>100.0 mM	"L " salts medium (7 d)	Burback et al. 1994
Rat	survival	LC_{50}	41.6 $g\cdot m^{-3}$	inhalation (4 h)	Mallinckrodt Inc. 1989
	survival	LD_{50}	3306 $mg\cdot kg^{-1}$ bw	ingestion (96 h)	

† The EC Endpoint represents the effects concentration as calculated by the CCME from the data presented by the authors.

APPENDIX IV. SELECTED STUDIES ON THE TOXICITY OF BENZENE TO TERRESTRIAL PLANTS AND SOIL INVERTEBRATES

Organism	**Effect**	**Endpoint**	**Effect concentration (mg·kg^{-1})**	**Test substrate (exposure period)**	**Reference**
Northern wheatgrass *Agropyron dasystachyum*	Shoot length	IC_{25}	404	Coarse, artificial sandy loam soil (14 d)	ESG 2002b
	Shoot wet mass	IC_{25}	260		
	Shoot dry mass	IC_{25}	110		
	Root length	IC_{25}	245		
	Root wet mass	IC_{25}	284		
	Root dry mass	IC_{25}	73		
Northern wheatgrass *Agropyron dasystachyum*	Shoot length	IC_{25}	936	Fine, field-collected clay loam soil (14 d)	Komex 2002 (based on data from ESG 2002b)
	Shoot wet mass	IC_{25}	565		
	Shoot dry mass	IC_{25}	495		
	Root length	IC_{25}	544		
	Root wet mass	IC_{25}	199		
	Root dry mass	IC_{25}	344		
Alfalfa *Medicago sativa*	Shoot length	IC_{25}	297	Coarse, artificial sandy loam soil (14 d)	ESG 2002b
	Shoot wet mass	IC_{25}	367		
	Shoot dry mass	IC_{25}	237		
	Root length	IC_{25}	276		
	Root wet mass	IC_{25}	680		
	Root dry mass	IC_{25}	235		
Alfalfa *Medicago sativa*	Shoot length	IC_{25}	391	Fine, field-collected clay loam soil (14 d)	Komex 2002 (based on data from ESG 2002b)
	Shoot wet mass	IC_{25}	409		
	Shoot dry mass	IC_{25}	280		
	Root length	IC_{25}	265		
	Root wet mass	IC_{25}	329		
	Root dry mass	IC_{25}	350		
Collembolan *Onychiurus folsomi*	Mortality	LC_{25}	63	Coarse, artificial sandy loam soil (14 d)	ESG 2002b
		NOEC	169		
		LOEC	282		
Collembolan *Onychiurus folsomi*	Mortality	LC_{25}	99	Fine, field-collected clay loam soil (14 d)	Komex 2002 (based on data from ESG 2002b)
Earthworm *Eisenia andrei*	Mortality	NOEC	0	Coarse, artificial sandy loam soil (14 d)	ESG 2002b
		LOEC	172		
Earthworm *Eisenia andrei*	Mortality	NOEC	63	Fine, field-collected clay loam soil (14 d)	Komex 2002 (based on data from ESG 2002b)
		LOEC	97		