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Canadian Soil Quality Guidelines
for Barium:
Protection of Human Health
Scientific Criteria Document

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NOTE TO READERS

The Canadian Council of Ministers of the Environment (CCME) is the primary minister-led intergovernmental forum for collective action on environmental issues of national and international concern.

This scientific supporting document provides the background information and rationale for the development of Canadian Environmental Soil Quality Guidelines for barium. The information in this document is current as of 2013, when the document was revised and updated. For additional scientific information regarding these guidelines, please contact:

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These guidelines are included as updates in the *Canadian Environmental Quality Guidelines*, which was published by CCME in October of 1999. The Canadian Environmental Quality Guidelines are available online at <http://ceqg-rcqe.ccme.ca/>.

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.

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ABSTRACT

Canadian environmental quality guidelines, developed under the auspices of Canadian Council of Ministers of the Environment (CCME), are numerical concentrations or narrative statements recommended to provide a healthy, *functioning* ecosystem capable of sustaining the existing and likely future uses of the site by ecological receptors and humans. Canadian soil quality guidelines can be used as the basis for consistent assessment and remediation of contaminated sites in Canada.

This report was prepared by Health Canada for CCME Soil Quality Guidelines Task Group. The Guidelines were derived according to procedures described in *A Protocol for the Derivation of Environmental and Human Health Soil Quality Guidelines* (CCME 2006). According to this protocol, both environmental and human health soil quality guidelines are developed and the lowest value generated from the two approaches for each of the four land uses is recommended by CCME as the Canadian Soil Quality Guidelines (CCME 2006). This scientific supporting document provides the background information and rationale for the calculation of human health-based soil quality guidelines for barium only.

This scientific supporting document provides the background information and rationale for the derivation of environmental and human health soil quality guidelines for barium. This document contains a review of the chemical and physical properties of barium, the sources and emissions in Canada, the distribution and behaviour of barium in the environment and the behaviour and effects of barium in humans and mammalian species. This information is used to derive soil quality guidelines for barium to protect human and ecological receptors in four types of land uses: agricultural, residential/parkland, commercial, and industrial.

CCME first attempted to develop Canadian Soil Quality Guidelines for barium in 1999 (CCME 1999). However, there were insufficient data to develop either environmental or human health guidelines, therefore, the Interim soil quality criteria (CCME 1991) were retained as the Canadian Soil Quality Guidelines for barium. The objective of this document is to update the 1999 Canadian Soil Quality Guidelines for barium with new a new attempt at deriving human health soil quality guidelines.

The environmental soil quality guidelines for barium were not updated in 2012. The conclusions of the 1999 barium Soil Quality Guidelines for Environmental Health remain in effect: “*In the case of barium, there are insufficient data and/or confounding factors in the existing data to derive the preliminary soil contact values or the nutrient and energy cycling checks. Thus, the interim soil quality criteria (CCME 1991) are recommended as the SQG_{ES} for all land uses (Table 2).*” For more information on the environmental soil quality guidelines for barium, and its effects on ecological receptors, consult EC (1999).

The human health soil quality guidelines for barium for each of the four land uses are: 6800 mg·kg⁻¹ soil for agricultural land use, 6800 mg·kg⁻¹ soil for residential/parkland land use, 10 000 mg·kg⁻¹ soil for commercial land use, and 96 000 mg·kg⁻¹ soil for industrial land use. These values are not applicable to barite and should not be used at sites where barite is naturally occurring. The human health soil quality guidelines were selected from direct human health-based soil quality guidelines for soil ingestion, soil particle inhalation and dermal contact for non-cancer effects, and the off-site migration check.

The Canadian Soil Quality Guidelines for the protection of environmental and human health, as recommended by Canadian Council of Ministers of the Environment (CCME 2006) are based on the lowest of the environmental soil quality guidelines or the human health-based soil quality guidelines. Therefore, the Soil Quality Guidelines for the protection of environmental and human health are based on the Interim remediation criteria for soil derived in 1991 (CCME 1991), and re-iterated by CCME in 1999. They are: 750 mg·kg⁻¹ soil for agricultural land use, 500 mg·kg⁻¹ soil for residential/parkland land use, 2000 mg·kg⁻¹ soil for commercial land use, and 2000 mg·kg⁻¹ soil for industrial land use.

RÉSUMÉ

Les recommandations canadiennes pour la qualité de l'environnement, élaborées sous les auspices du Conseil canadien des ministres de l'environnement (CCME), sont des limites quantitatives ou descriptives recommandées dans le but d'assurer un écosystème sain, capable de supporter les utilisations actuelles et probables du site par les récepteurs écologiques et humains. Les recommandations canadiennes pour la qualité des sols peuvent être utilisées comme base pour l'uniformisation des processus d'évaluation et d'assainissement des terrains contaminés au Canada.

Le présent document a été préparé par Santé Canada pour le Groupe de travail sur les recommandations pour la qualité des sols du CCME. Les recommandations ont été élaborées selon les procédures décrites dans le *Protocole d'élaboration de recommandations pour la qualité des sols en fonction de l'environnement et de la santé humaine* (CCME 2006). Conformément à ce protocole, les recommandations pour la qualité des sols visant la protection de l'environnement et de la santé humaine sont développées et la plus petite valeur obtenue de ces deux procédures, pour chacune des quatre types de vocation des terrains, est recommandée par le CCME comme étant la recommandation canadienne pour la qualité des sols (CCME 2006). Ce document technique contient uniquement l'information de fond et la justification pour la dérivation des recommandations pour la qualité des sols pour la protection de la santé humaine.

Ce document scientifique contient l'information pertinente sur les données de fond et la justification pour la détermination des recommandations pour la qualité des sols pour le baryum. Ce document contient une revue de l'information sur les propriétés chimiques et physiques du baryum, sur les sources et émissions au Canada, sur la distribution et le comportement du baryum dans l'environnement et sur son comportement et ses effets chez les humains et les mammifères. Cette information est utilisée pour l'élaboration des recommandations pour la qualité des sols relatives au baryum afin de protéger les récepteurs écologiques et humains dans quatre types de vocation des terrains: agricole, résidentielle/parc, commerciale et industrielle.

Les recommandations pour la qualité des sols pour la protection de l'environnement pour le baryum n'ont pas été mises à jour en 2012. Les conclusions des Recommandations pour la qualité des sols pour la protection de l'environnement de 1999 demeurent donc en vigueur : "*Dans le cas du baryum, les données sont insuffisantes ou des facteurs de confusion dans ces données empêchent le calcul des valeurs pour le contact direct avec le sol ou le cycle des nutriments et de l'énergie. Ainsi, on recommande l'utilisation des critères intérimaires (CCME 1991) comme SQG-E pour toutes les vocations de terrain (tableau 2).*" Pour de plus amples renseignements sur les recommandations pour la qualité des sols pour la protection de l'environnement pour le baryum et ses effets sur les récepteurs écologiques veuillez consulter EC (1999).

Les recommandations pour la qualité des sols visant la protection de la santé humaine établies pour le baryum pour chacune des quatre vocations des terrains sont de : 6800 mg·kg⁻¹ pour des terrains à vocation agricole, 6800 mg·kg⁻¹ pour les terrains à vocation résidentielle/parc, 10 000 mg·kg⁻¹ pour les terrains à vocation commerciale et 96 000 mg kg⁻¹ pour les terrains à vocation industrielle. Ces valeurs ne sont pas applicables à la barite et ne devraient pas être utilisés pour

les sites où la barite est présente naturellement dans les sols. Les recommandations pour la qualité des sols visant la protection de la santé humaine ont été sélectionnées parmi les voies d'exposition humaines suivantes : recommandations pour la qualité des sols relatives au contact direct pour l'ingestion, l'inhalation des particules du sol et le contact dermique pour les effets non-cancérogènes, et la migration hors site de sol et de poussière provenant des terrains commerciaux ou industriels.

Les recommandations canadiennes pour la qualité des sols visant la protection de l'environnement et de la santé humaine, telles que recommandées par le Conseil canadien des ministres de l'environnement (CCME 2006) sont basées sur les recommandations les plus faibles des recommandations visant la protection de l'environnement ou de la santé humaine. Par conséquent, elles sont : $50 \text{ mg}\cdot\text{kg}^{-1}$ pour les terrains à vocation agricole, $50 \text{ mg}\cdot\text{kg}^{-1}$ pour les terrains à vocation résidentielle/parc, $94 \text{ mg}\cdot\text{kg}^{-1}$ pour les terrains à vocation commerciale et $94 \text{ mg}\cdot\text{kg}^{-1}$ pour les terrains à vocation industrielle. Les présentes recommandations pour la qualité des sols pour le baryum remplacent les recommandations pour la qualité des sols, développées en 1999 (Environnement Canada 1999), et publiées la même année par CCME (1999), ainsi que les critères provisoires pour l'assainissement du sol pour le baryum (CCME 1991).

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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 CCME Soil Quality Guidelines Task Group are gratefully acknowledged for their scientific advice and reviews.

1. INTRODUCTION

Canadian Soil Quality Guidelines are numerical concentrations or narrative statements that specify levels of toxic substances or other parameters in soil that are recommended to maintain, improve or protect environmental quality and human health. They are developed using formal protocols to ensure nationally consistent, scientifically defensible values. The guidelines are nationally endorsed through the Canadian Council of Ministers of the Environment (CCME).

The development of Canadian Soil Quality Guidelines was initiated through the National Contaminated Sites Remediation Program (NCSRP) in 1991 by 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 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 CCME (CCME 1996 revised in 2007). 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 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 CCME in October of 1999 and updated regularly since. The interim soil quality criteria (CCME 1991) should be used only when soil quality guidelines based on CCME protocol have not yet been developed for a given chemical.

This report reviews the sources and emissions of barium, its distribution and behaviour in the environment and its toxicological effects on humans and experimental animals. Guidelines are calculated according to *A Protocol for the Derivation of Environmental and Human Health Soil Quality Guidelines* (CCME 2006) for various land uses: agriculture, residential/parkland, commercial and industrial. In addition, various check mechanisms considering indirect pathways of exposure (i.e. nutrient and energy cycling check and off-site migration of substances via wind and water (erosion) are used to provide protection for resources and receptors not otherwise considered in the calculation of soil guidelines.

The following calculated values should be considered for general guidance purposes. Since the guidelines may be applied differently in various jurisdictions, the reader should consult appropriate authorities for guidance in the application of these guidelines. Every attempt was made to provide a conservative estimate that could be applied to any area in Canada. Soil quality guidelines are calculated 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 or lifestyle choices. These non-scientific factors are to be considered by site managers at the site-specific level as part of the risk management process. Due to geological conditions, it is possible that natural enrichment will result in exceedances of the soil quality guidelines. Thus, such exceedances do not automatically imply that the ecosystem is compromised. The guideline represents a limit below which no adverse impacts are expected, but site-specific information, such as local background concentrations, should always be considered in the application of these guidelines.

2. BACKGROUND INFORMATION

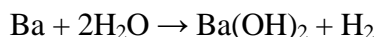
2.1 Physical and Chemical Properties

Barium (Ba) CAS 7440-39-3 is an alkaline-earth metal. It is a soft, ductile, silvery-white metal (Group IIA of the periodic table) with an atomic number of 56 and a relative molecular mass of 137.33. It has a specific gravity of 3.6 at 25°C, melts at 727° C and vaporises at 1897°C (Haynes 2011). Barium is chemically similar to calcium, physically similar to lead and possesses an effective ionic radii similar to potassium (I) (Martin 1986). The physical and chemical properties of barium and some barium compounds are summarised in Table 1.

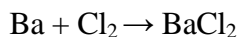
Although 25 barium isotopes have been identified, barium occurs as a mixture of 7 stable isotopes with weights of 130, 132, 134, 135, 135, 137 and 138 and abundances (as %) of 0.101, 0.097, 2.42, 6.59, 7.81, 11.32 and 71.66, respectively (WHO 1990, Boffito 1991).

Barium has a valence electron configuration and characteristically forms divalent compounds. It is an extremely reactive metal, and its compounds possess large free energies of formation. At room temperature, it combines readily and exothermically with oxygen and the halogens. Barium reacts vigorously with water, liberating hydrogen and forming barium hydroxide, Ba(OH)₂ (CAS 17194-00-2). At elevated temperatures, barium combines with hydrogen to form barium hydride, BaH₂ (CAS 13477-09-3) and with nitrogen to form barium nitride, Ba₃N₂ (CAS 12047-79-9). When combined with nitrogen and carbon, barium forms barium cyanide that is thermally stable. Finely divided barium is susceptible to rapid, violent exothermic reactions with atmospheric oxygen. Therefore, in powdered form it must be considered pyrophoric and very dangerous to handle in the presence of air or other oxidising gases. Barium powder must be stored under dry argon or helium to avoid the possibility of violent explosions (Boffito 1991).

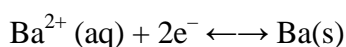
Barium reacts violently with dilute acids, evolving hydrogen:



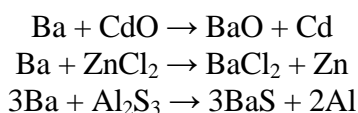
Reactions with halogens give barium halides:



Barium is a strong reducing agent. The E° for the reaction is -2.90 V:



Barium reduces oxides, chlorides and sulfides of less reactive metals producing the corresponding metals; e.g.



When heated with nitrogen in the presence of carbon, it forms barium cyanide:



Barium combines with most metals, forming a wide range of alloys and intermetallic compounds. Among the phase systems that have been better characterised are those with Ag, Al, Bi, Hg, Pb, Sn, Zn and the other Group 2 metals (Boffito 1991). Additionally, many barium compounds are readily reduced by Mg and Ca which results in the production of barium alloys, as opposed to the formation of pure barium (Boffito 1991).

Since barium quickly oxidises in air, it is difficult to obtain the free metal and as such it does not occur naturally. The metal is primarily extracted from barite. However, barite cannot be used directly for the preparation of barium compounds or barium metal because it is so insoluble (Pradyot 2003).

The barium salts of acetate, hydroxide, silicate, chlorate, nitrate, thiocyanate, cyanide, oxide and halide are soluble in water. The barium salts of arsenate, carbonate, citrate, fluoride, oxalate and tartrate are sparingly soluble in water but soluble in acids. Barium chromate and phosphate are insoluble in water but soluble in acids whereas barium sulphate is insoluble in water and only sparingly soluble in acids requiring strong H_2SO_4 to dissolve. All barium salts, except sulphate, exhibit increasing solubility with decreasing pH (WHO 1990).

Organometallic compounds of barium are ionic in nature and readily hydrolyse in water. Barium will form complex compounds with chloride, hydroxide and nitrate anions but these compounds are weak and contribute very little to total barium concentrations.

Additionally, to a limited extent, barium forms complexes with natural organics. Complex formation does not readily occur because the amines formed are unstable and the β -diketones and alcoholates are not well characterised (WHO 1990).

Table 1. Physical and chemical properties of some barium compounds

PROPERTY	COMPOUND						
	Barium	Barium carbonate (witherite)	Barium chloride	Barium hydroxide	Barium oxide	Barium sulphate (barite)	Barium sulphide
Chemical Formula	Ba	BaCO ₃	BaCl ₂	Ba(OH) ₂	BaO	BaSO ₄	BaS
CAS Registry Number	7440-39-3	513-77-9	10361-37-2	17194-00-2	1304-28-5	7727-43-7	21109-95-5
Molecular Weight	137.33	197.34	208.23	171.34	153.33	233.39	169.39
Physical Description	Silvery yellow metal (cubic)	White orthorhombic crystals	White orthorhombic crystals; hygroscopic	White powder	White, yellowish powder; cubic and hexagonal	White, orthorhombic crystals	Colourless cubic crystals or gray powder
Melting Point (°C)	727	Decomposes at 1380; 1555 (high pressure)	961	408	1973	1580	2227
Boiling Point (°C)	1897	No data	1560	No data	No data	No data	No data
Density (g·cm ³ @ 25 °C and 101.325 kPa)	3.6	4.3	3.9	3.7	5.72 (cubic)	4.5	4.3
Solubility	Reacts with water Slightly soluble in ethanol	0.0014g per 100g water @ 20 °C Soluble in dilute HCl, HNO ₃ , acetic acid, NH ₄ Cl and NH ₄ NO ₃ solutions and alcohol	37g/100g @ 25 °C	4.91g/100g water @ 25 °C Soluble in methanol	1.5g/100g water @ 20 °C Soluble in ethanol and dilute acid. Insoluble in acetone	0.00031g/100g water @ 20 °C Insoluble in ethanol	8.49 g/100g @ 25 °C

* Source: CRC Handbook (Haynes 2011).

2.2 Geochemical Occurrence

Barium was discovered in 1808 by Sir Humphrey Davy. Barium metal does not occur free in nature; however, its compounds occur in small but widely distributed amounts in the earth's crust, especially in igneous rocks, sandstone and shale (Boffito 1991). It occurs in underground deposits as barite or heavy spar (as sulphate) and in witherite (as carbonate) (Pradyot 2003). Barium has been identified in over 80 minerals (DiBello *et al.* 1991).

Barium occurs in the earth's crust with an average concentration of 425 mg/kg (Taylor 1964). Barium compounds are widely distributed especially in igneous, sedimentary and metamorphic rocks (Boffito 1991; DiBello *et al.* 1991). The average barium concentration in basalt is 250 mg/kg and in granite is 600 mg/kg (Taylor 1964). Barium is found in coal at concentrations up to 3000 mg/kg and in fuel oils at varying concentrations (WHO 1990). The concentration of barium in Canadian feed-coals varies between 41.3 and 615 mg/kg (Goordazi 2002). The element also is found in sea water at 13 µg/L concentrations.

Barite deposits have been found in all provinces except Alberta, Saskatchewan and Prince Edward Island. More than 150 deposits have been identified in Canada, many of them are small and of low commercial interest. However, some have been developed into producing mines. There are four main barite orebodies in Canada. These include: the Walton orebody in Nova Scotia; the Giant Mascot and Mineral King orebodies in British Columbia; and the Buchans orebody in Newfoundland and Labrador (Dumont 2007).

The only other commercially available barium mineral is witherite (barium carbonate, BaCO₃). Witherite is a rare mineral because it easily alters to barite. This occurs when sulphuric acid from sulphide minerals dissolves the witherite and the sulphur combines with the barium to form barite. However, in some localities such as Illinois, USA, witherite occurs in relative abundance as calcite loses calcium to barium creating witherite (Dumont 2007). With respect to witherite in Canada, there are not many localities for this mineral; however, a small deposit exists in Thunder Bay, Ontario (Dumont 2007).

2.3 Analytical Methods

The resultant concentration of barium in a given soil sample varies based on extraction procedure; as well as, the method of analysis (Alloway 1990; Garrett 2004 *pers. com.*; Lutwick 1994 *pers. com.*; Pastorek 1995 *pers. com.*). For example, the use of *aqua regia* (1HNO₃:3HCl) digestion and 6010 Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES) analysis releases the biologically relevant barium present in soluble salts, organic matter and that adsorbed to soil particles as well as the barium present in some weak silicates. The method leaves most silicates and stable mineral matrices intact (Garrett 2004 *pers. com.*). Instrumental photon activation and emission spectrographic methods of analysis coupled with extraction using HF/HCl/HNO₃/HClO₄ are required to determine the total barium content of soil (CCME 1999).

A range of extraction methodologies have been used to generate digests for the analysis of barium. The methods vary in the amount of barium that they extract. The US EPA sample preparation methods for extraction of barium from sample materials include: EPA Method 3050B *Acid Digestion of Sediments, Sludges, and Soils* (hydrochloric acid digestion); EPA Method 3005A *Acid*

Digestion of Waters for Total Recoverable or Dissolved Metals for Analysis for FLAA or ICP Spectroscopy (nitric acid digestion) for extraction from surface and groundwater samples; and EPA Method 3015 *Microwave Assisted Acid Digestion of Aqueous Samples and Extracts*.

The analytical method recommended by CCME (1993a,b) for analysis of barium is sample digestion using with HNO₃/HCl followed by US EPA Method 6010 ICP-AES analysis. This method is applicable to the determination of barium in groundwater, soils, sludges, sediments and other solids and as discussed above quantify the biologically relevant barium in a sample. The estimated instrumental detection limit is 2 µg/L. The US EPA analytical method 6020 ICP-MS is a more sensitive technique, with an estimated detection limit of <0.02 µg/L. (HSDB 2003; US EPA 2003). This method is applicable to groundwater, aqueous samples, industrial wastes, soils, sludges, sediments and other solid wastes. Preliminary treatment by acid digestion is required for all samples (with the exception of water) to determine total barium content. Water samples must be filtered and acid-preserved prior to analysis to determine dissolved barium content (US EPA 2003).

Special Considerations for Barite Contaminated Sites

As discussed in the next section, barite is commonly used in the oil and gas industry in drilling muds. Barite is highly insoluble; therefore, barium within barite (BaSO₄) will not necessarily be released to the environment (AENV 2009a). The safe management of barite can be obtained at higher concentrations than that of soluble barium compounds in soil (AENV 2009a). Therefore, for practical reasons, Alberta Environment (AENV) and the British Columbia Ministry of Environment (BCME) have developed barite guidelines to be used only at barite contaminated sites (AENV 2009a; BCME 2009). These guidelines outline specific extraction methods to address the difference in total versus extractable barium at barite contaminated sites. There is no analytical method specific for the quantification barite in soil (AENV 2009b). Strong acid digestion techniques used specifically for analysis of total metals in soils can result in considerable over-estimation of soluble barium concentrations in soil containing barite (BCME 2009).

Both AENV's Soil Remediation Guidelines for Barite: Environmental Health and Human Health (2009a) and BCME's Protocol 14 for Contaminated Sites – Requirement for Determining Barite (2009) recommend a calcium chloride extraction method to assess extractable barium in soil samples collected from barite sites (AENV 2009b; BCME 2009). In B.C., the method is referred to as Analytical Method 9 – Soluble Barium by Calcium Chloride Extraction (BCME 2007).

Further discussion regarding characterising barite contaminated sites with respect to historical use, background soil data collection and applying the guideline values is discussed in the above mentioned Alberta and British Columbia guidance documents.

Special Considerations for Barium Analysis in Water

US EPA (2008) recommends the digestion of water and other aqueous samples follow Methods 3005A, 3010A, 3015 or 3020. These methods are based on acid digestion or microwave-assisted acid digestion for analysis of total recoverable, dissolved or total metals (including barium). These digestion methods are suitable preparation for analysis by US EPA (2008) Methods 7080A and/or 7081 using FLAA, GFAA, ICP-AES or ICP-MS.

Parts-per-trillion (sub µg/L) levels of barium in seawater and freshwater have been detected using GFAAS. The advantages of the GFAAS and FAAS sensitive techniques include the use of relatively simple and inexpensive instrumentation along with high accuracy and precision. The GFAAS technique uses a smaller amount of sample and is more sensitive than the FAAS technique for determining barium in aqueous media.

According to Ontario Ministry of the Environment, groundwater and surface water should be analysed directly by ICP-MS or GF-AAS per Method Reference: MOE-E3051 (OMOE 2004).

Additional Considerations for Barium Analysis in Air

Methods to measure barium compounds in air include an ashing procedure prior to analysing by FAAS or gravimetric assessment of respirable dust samples (CICAD 2001). NIOSH method (7056) uses FAAS as the technique to quantify barium in air.

AAS has also been used to measure barium in air (ATSDR 1992). Barium has been detected in air at 20 ppb using AAS (WHO 1990).

NIOSH Method 7300 is a technique recommended for analysing soluble barium compounds in air with a limit of detection of 0.005 µg per sample (approximately 0.005 µg/m³) which is 400 times less than the detection limit for other analysis techniques (NIOSH 2003).

2.4 Production and Uses in Canada

The global barite production for 2006 was estimated to be over 7.9 Mtonnes with China (4.4 Mtonnes), India (1.0 Mtonnes) and the United States (589 000 tonnes) leading the production. Canadian production of barite and witherite in 2007 was estimated at close to 7196 tonnes which is down from 19 597 tonnes in 1996 (Dumont 2007). However, Dumont (2007) estimated 68 971 tonnes of barite and witerite were used in Canada in 2007 (approximately 62 172 tonnes were imported).

There are four producers of barite in Canada: Nystone Chemicals Ltd. in Nova Scotia; Extender Minerals of Canada Ltd. in Ontario; Highwood Resources Ltd. and Fireside Minerals Ltd. in British Columbia. Highwood is the largest producer in terms of volume followed by Fireside, Extender and Nystone (Dumont 2007).

Highwood operates an underground mine in Parson, British Columbia and a processing plant in Lethbridge, Alberta. Its product is used primarily in drilling muds and also in paints and plastics (Dumont 2007).

Fireside operates a high-grade white barite mine in British Columbia near the Yukon border and a processing plant in Watson Lake, Yukon. The barite produced is suitable for filler applications or for use in drilling mud (Dumont 2007).

Extender operates an underground (brown barite vein deposit-type) mine and processing plant close to Matachewan, Ontario near Kirkland Lake. The product is graded at 93-97% barite and is used in paints, plastics, rubber foam fillers, tiles and brake linings (Dumont 2007).

Nystone operates an open-pit mine in Brookfield, Nova Scotia, where the ore is crushed, screened and processed at a plant in Debert, Nova Scotia. The company produces a high-value pharmaceutical-grade barite with a minimum purity of 97.5% (Dumont 2007).

Therapex of Montréal, produces high-purity barite for pharmaceutical use (Boucher 1997).

Barium minerals and compounds are widely used in a number of key industries. Generally the physical and chemical properties of the raw mineral (particle size, specific gravity, reflective properties, degree of whiteness and purity) will determine the application. More than 90% of the barium used is in the form of barite ore after preliminary beneficiation (washing, flotation, jigging or magnetic separation) (DiBello *et al.* 1991). Globally, 85% of barite is used as a drilling fluid additive, 10% is used in the chemical sector and 5% as fillers (Dumont 2007).

Barite is also used in other applications in much smaller quantities. The ability of barite to absorb and reduce radiation from x-rays and gamma rays make it useful as a replacement for lead in shields for nuclear reactors and in faceplates for televisions and computer monitors (NRCan 2003).

Barite is added to paints to provide bulk, control pigment settling, improve viscosity, improve application properties and improve surface finish. It is used as filler in plastics and rubber products. Also, it imparts sound-deadening characteristics and improves processing qualities when used as a backing in floor mats and carpets. In clutch pads and brake lining of vehicles, the barite filler acts as a heat sink. It is also used as an ingredient in the manufacture of glass and ceramics, where it is used as a flux and increases the lustre and brilliance of glass, improves workability and can act as a decolouriser. Other industrial uses of barite include product manufacturing (bowling balls, ink, oilcloth, photographic paper, artificial ivory, cellophane, wallpaper, adhesives, sealants, polymeric fibres and resins); sugar refining; metal casting (mold-release compounds); chocolate manufacturing (forming agent); heavy concrete production (radioactive shield); firework production (produces the colour green); and pond repair (used to stop leaks in lined ponds that cannot be drained) (AENV 2004).

In addition, barite is used as a feedstock for the production of other barium chemicals. The high density, low solubility and low toxicity of barite allows for its use in X-ray diagnostic tests to photograph the gastro-intestinal tract (DiBello *et al.* 1991; NRCan 2003; AENV 2004). Thermal reduction of barite via the black ash process, leads to the commercial production of barium carbonate (DiBello *et al.* 1991). Barium carbonate is used predominantly in the manufacture of glass, clay and brick products. Some barium carbonate is also used in other processes such as the manufacturing of barium ferrites (used to make magnets for small motors and in the production of photographic papers).

Barium hydroxide is used to refine sugar from molasses, manufacture polyurethane foams and acts as a stabiliser in plastics, waterproof and fire-proof sizings and coatings (DiBello *et al.* 1991).

Barium nitrate is used in the pyrotechnics industry in the production of green flares (i.e. fireworks) and tracer bullets (DiBello *et al.* 1991).

Barium metal produced from barium carbonate by calcination with carbon is used to remove gas traces from vacuum and television picture tubes. It is also used to improve the performance of acid battery lead alloy grids, as a lubricant in vacuum x-ray tubes and as a component in various nodulising and deoxidising alloys (Boffito 1991). Barium is used in the production of agricultural insecticides, rodenticides, herbicides and germicides. It is also used in the manufacturing of pharmaceutical products such as vitamins, hormones, blood coagulants and cosmetics such as depilatories (Reeves 1986).

Barium alloys are used in iron production to control the shape of nodular graphite inclusions and as reducing agents to remove oxygen from molten steel, copper and other metals. Organometallic barium compounds are currently used to reduce black smoke emissions from diesel fuels (WHO 1990).

The main uses and applications of other barium compounds are concisely outlined in WHO (1990).

2.5 Sources and Concentrations in the Canadian Environment

The assessment of soil quality for metals must take into consideration regional variations in background concentrations of metals in Canada. The background concentrations and environmental fate of metals strongly depend on geological and biological characteristics; therefore, any assessment of potential risks associated with metals should take into consideration regional differences in metal content in the natural environment (Chapman and Wang 2000).

Relatively high concentrations of metals can occur naturally in Canadian soils, stream sediments and water blurring the distinction between anthropogenic pollution versus naturally occurring bodies of ore (Environment Canada 1996). Soils and sediments reflect the composition of parent material, resulting in higher metal concentrations in mineralised areas (Wilson *et al.* 1998). Mining districts are characterised by naturally occurring metals in soil, sediment, rock and water at concentrations that could result in their classification as "contaminated sites" (Painter *et al.* 1994). In the determination of anthropogenic metal contamination of soils, no single guideline concentration can adequately represent the variance in background concentrations across Canada (Painter *et al.* 1994; Chapman and Wang 2000).

Data representing the background or ambient concentrations of total barium in the Canadian environment are presented for ambient air, indoor air, indoor dust, soil, surface water, groundwater, drinking water, sediment, biota as human food, commercial foods, consumer products, human tissues/biological fluids and rain/snow/fog. In some cases, the data reported came from published sources; however, the majority of information was provided as government databases. The monitoring data provided here are dynamic and should be considered representative of the best available information for the specified time period.

Due to its abundance in soils, barium can be present in air masses in areas with high natural dust levels (WHO 1990). However, barium concentrations in air are typically the result of anthropogenic activities (WHO 1990; ATSDR 2007). Virtually every industry such as: electric power generating stations; heating/industrial plants; gasoline combustion; non-ferrous metal smelters; kiln operations in cement plants; and refuse incineration will release heavy metals to the atmospheric, aquatic and terrestrial ecosystems (Wilson *et al.* 1998).

Although barium is not currently being measured under the National Pollutant Release Inventory (NPRI), some relevant emissions data exist. Reznik and Troy (1978) estimated chemical dryers and calciners used during in the processing of barium carbonate, chloride and hydroxide produce uncontrolled particulate emissions at 5000 mg/kg of the final product and controlled particulate emissions at 250 mg/kg of the final product (ATSDR 2007). Together the uncontrolled and controlled emissions from this industry are estimated to be 160 metric tons per year (ATSDR 2007). Coal combustion releases ash containing barium at 100 to 5000 mg/kg (WHO 1990).

Less significant barium emissions occur from the ash released by heavy fuel oil (50 mg/kg dry wt) and peat (83 mg/kg dry wt) combustion in power plants (Häsänen *et al.* 1986). Emissions during mining, refining and processing barium ore occur during loading, unloading, stock-piling, materials handling, grinding and refining of the ore. The plastics and glass industries are important sources of barium emissions (WHO 1990). In 1969, it was estimated that the glass production industry used 41 000 tons of barium resulting in 40 tons of barium emissions in the United States (Davis 1972). Barium emissions from petroleum product use (barium is an additive in greases, transmission fluids, detergents and rust/corrosion inhibitors) are known to occur; however, data are not reliable enough to estimate amounts released to the environment (Pacyna 1986). Hildemann *et al.* (1991) reported no barium in heavy-duty diesel truck emissions (n=2). However, Pierson *et al.* (1981) found that more than 90% of the added barium in diesel fuels was emitted as barium sulphate in exhaust.

The release of radioactive barium upon atmospheric detonation of nuclear devices has been reported by French (1963); however, contributions to overall atmospheric emissions are reported to be minimal due to the short half-life, low concentrations of the radionuclide and the infrequency of such events (WHO 1990).

2.5.1 Ambient Air

The National Air Pollution Surveillance (NAPS) Network is a joint program of the federal and provincial governments which monitors and assesses the quality of the ambient air in Canadian urban centres. Particulate matter with aerodynamic diameters less than 10 µm (PM₁₀) and less than 2.5 µm (PM_{2.5}) are measured and sample filters are analysed for 50 elements (including barium), 14 inorganic and organic anions and 11 inorganic cations (Environment Canada 2011).

The mean barium concentration in Canadian ambient air is estimated to be 1.9 ng/m³ (arithmetic mean, SD=3.2, N=3054, range=0-30 ng/m³) (Health Canada 2011). This mean is based on NAPS data (PM_{2.5} fraction analysed by ICP-MS following acid digestion) collected from 2003 to 2009 from British Columbia, Ontario, Quebec and New Brunswick from urban and rural centers. ICP-MS data are not currently available for the remaining provinces and territories. These data were also used to develop the barium EDI values for inhalation of ambient air used in the SQG calculation. The EDI methodology is further discussed in Section 5.2 of this document.

A summary of available environmental concentrations used in the previous soil quality guideline for ambient air is provided in Appendix 1.

2.5.2 Indoor Air

There are a limited number of studies pertaining to barium concentrations in indoor air. Additionally, there is no Canadian database for indoor air concentrations (Rasmussen *et al.* 2006). Due to the small data set available for Canada, data from the U.S. were also included in the data set used to determine background indoor air concentrations.

Alberta Heath (1998) conducted an air quality study in High Level, Alberta. This study included the collection of 24 hour outdoor, indoor and personal air samples for 10 days at two homes. Additional outdoor samples were collected at a central location to the homes at the same frequency and duration. At each location both PM₁₀ and PM_{2.5} samples were collected. The average indoor barium concentrations for the two homes were 9 ng/m³ in the PM₁₀ fraction and 5.02 ng/m³ in the PM_{2.5} fraction. For comparison, the average outdoor barium concentration was 15.88 ng/m³ (PM₁₀) and 2.3 ng/m³ (PM_{2.5}). The average personal concentration was 25.06 ng/m³ (PM₁₀) and 6.86 ng/m³ (PM_{2.5}).

Graney *et al.* (2004) collected indoor and personal air samples (PM_{2.5}) at a retirement facility in Baltimore, MD, U.S.A. Ten daily sample sets (one indoor and one personal air sample) were collected. The median concentration of barium was 0.33 ng/m³ for indoor air samples and 0.68 ng/m³ for personal air samples. Analysis was completed by ICP-MS following partial digestion.

Based on the two studies described above, the background concentration in indoor air was determined to be 2.7 ng/m³ (arithmetic mean, SD=4.2, N=40) (Health Canada 2011). These data were used to develop the barium EDI values for inhalation of indoor air used in the SQG calculation. The EDI methodology is further discussed in Section 5.2 of this document.

A summary of available environmental concentrations in indoor air is provided in Appendix 1.

2.5.3 Indoor Dust

Similar to indoor air, there are limited data regarding the concentration of barium in indoor dust. One study is available which provides measured values for samples collected within the City of Ottawa (Rasmussen *et al.* 2001). A multi-element profile of house dust in relation to exterior dust and soils was conducted for the City of Ottawa, an urban centre with a low concentration of heavy industries (Rasmussen *et al.* 2001). Random samples of house dust; as well as, street dust and garden soil (within 15 m of each residence) were collected from 10 zones in the City of Ottawa. Metal content was determined by ICP-MS; the barium detection limit was 1 mg/kg. A wide range of barium concentrations were reported in house dust (n=48), from 190 to 1480 mg/kg with a mean of 492 mg/kg and a median of 454 mg/kg (dry weight).

The National Human Exposure Assessment Survey (NHEXAS) is a program initiated by the Office of Research and Development of the US EPA in order to better understand human exposure to toxic chemicals from various media sources in the United States (US EPA 2009). Data from this survey for Arizona (data from Region V and Maryland were not available) were included in the development of the Canadian background indoor dust concentration. The inclusion of American data to develop Canadian background concentrations is acceptable based on an uncertainty analysis (Health Canada 2011).

Based on the above mentioned Canadian study and NHEXAS database, the background barium concentration in Canadian indoor dust was estimated to be 305.3 mg/kg (arithmetic mean, SD=311.3, N=165) (Health Canada 2011). This value is used to calculate the estimated daily intake (EDI) for barium. It should be noted, loading values (i.e. mg/m²) were not included the calculation of the background concentration of barium in indoor house dust.

A summary of available environmental concentrations in indoor dust is provided in Appendix 1.

2.5.4 Soil

Barium is ubiquitous in soils with concentrations ranging from 15 to 3000 mg/kg (ATSDR 1992). However, near barite deposits, soil barium concentrations can be as high as 37 000 mg/kg (Adriano 1986).

The Geological Survey of Canada (GSC) houses a large geochemical background soil database which was used to develop the background concentration of barium in soil for Canada. While barium concentrations in soil throughout Canada vary based on geology and anthropogenic inputs; a single background soil concentration is required to develop soil quality guideline for use throughout Canada. The mean concentration of barium in Canadian soil is estimated to be 140 mg/kg (arithmetic mean, SD=120, N=7397) (Grunsky 2010) for the purpose of creating an SQG. This value is based on GSC data obtained from till samples (<63µm) that were analysed by AAS/ICP-ES following aqua-regia digestion (partial digestion by HCl and HNO₃). These till samples were obtained from Newfoundland/Labrador, New Brunswick, Quebec, Nunavut, Northwest Territories, Manitoba, Saskatchewan, Alberta and British Columbia. These data were used to develop the barium EDI values used in the SQG calculation. The EDI methodology is further discussed in Section 5.2 of this document.

It is recognised that till may not be representative of surficial soils to which people are exposed since there is limited anthropogenic input to till. The background concentration of barium in till were used to represent background concentrations of barium in Canada without anthropogenic input. These concentrations were obtained by the GSC as discussed above and are thought to be representative of Canadian background. For site-specific assessments, local background concentrations of barium in surface soils may be preferable, both to estimate the background soil concentration (BSC) and estimated daily intake (EDI) for barium.

Surface soil data are not nationally representative at this point and hence have not been used to estimate background soil concentrations. However, Maritime soil survey data are available for the PH, A, B and C horizons obtained through the NASGLP (North American Soil Geochemical Landscape Project) which is available through the GSC (coverage for New Brunswick, Nova Scotia and Prince Edward Island). Concentrations represent the <2mm fraction milled, analysed by ICP-ES following EPA 3050B digestion; therefore, the resultant concentrations are not directly comparable to the national till data reported by Grunsky (2010) (<63µm fraction analysed by AAS/ICP-ES following aqua regia digestion as discussed above).

From the NASGLP data, the mean concentration in the PH horizon is 79.7 mg/kg (SD=83.4, N=184). The mean concentration in the A horizon is 87.3 mg/kg (SD=76, N=156). The mean

concentration in the B horizon is 39.2 mg/kg (SD=25.8, N=183). The mean concentration in the C horizon is 46.8 mg/kg (SD=32.8, N=176) (Grunsky 2010).

Typically barium in soil recovered by aqua regia digestion is quite variable since barite is not fully dissolved by this digestion method (McNeil and Garrett 2010) Therefore, aqua regia digestion will result in lower concentrations of barium than an analysis using a total digest.

Localised Canadian soil concentrations from previous soil quality guidelines for barium in soils are summarised in Appendix 1 and discussed below. The reported concentrations may not be directly comparable, as methods of sample digestion will influence the degree to which barium is leached from the soil matrix as discussed in previous section regarding analytical methods.

The mean barium concentration in 1128 samples of soil from Alberta was 325 mg/kg following strong acid digestion (AENV 2009a). This value is used as a reference background concentration in Alberta (AENV 2009a).

The barium background soil quality estimates reported for Ontario in the *Guideline for Use at Contaminated Sites* were 190 mg/kg for agricultural land use and 210 mg/kg for all other land uses (OMOE 1997).

In Ottawa, barium concentrations (dry weight) in garden soil (n=50) ranged from 609 to 903 mg/kg (mean 766 mg/kg) and in street dust (n=45) ranged from 153 to 714 mg/kg (mean 576 mg/kg) (Rasmussen *et al.* 2001)

Background soil concentrations estimated for 5 regions in Quebec (MDDEP 2010) for barium were reported to be 200 mg/kg in the St. Lawrence Lowlands, Grenville, Superior and Rae regions, 245 mg/kg in the Labrador Trough region and 265 mg/kg in the Appalachian region.

In New Brunswick, Pilgrim and Schroeder 1997 reported barium concentrations (dry weight) in soil samples (depths not reported) from 9 urban gardens in East St. John, 2 urban gardens in West St. John and 1 rural garden in Fredericton (by ICP-MS). Mean barium concentrations were comparable across the locations sampled: East St. John (276 ± 28 mg/kg, n=18), West St. John (302 ± 25 mg/kg, n=4) and rural locations (344 ± 9 mg/kg, n=2)

In Trail, B.C., soil studies conducted in 1989 from the area around the Cominco lead smelter indicate that they were not impacted by barium (Kelly *et al.* 1991). Sandbox soils (35 samples) contained barium concentrations from 28.1 to 305 mg/kg with an arithmetic mean concentration of 111.0 ± 55.1 mg/kg. Park soils (41 samples) ranged from 56.4 to 341 mg/kg with an arithmetic mean of 117.2 ± 53.9 mg/kg. The concentration in 122 samples of residential soils ranged from 67-436 mg/kg with an arithmetic mean of 208.8 ± 85.9 mg/kg. These samples were analysed by ultrasonic nebulisation-ICP following digestion with HF-HClO₄-HNO₃.

Gietl *et al.* (2010) reported that at traffic-influenced sites, brake wear appears to be the main source of barium.

2.5.5 Surface Water

Barium concentrations were analysed in water samples collected from the Great Lakes (Rossmann and Barres 1988). Median concentrations ranged from 18 to 53 µg/L for dissolved

barium; 0.025 to 5.3 µg/L for barium in the particulate fraction; and 18 to 52 µg/L for total barium (Rossmann and Barres 1988).

Surface water data (1997 to 2003) for five river basins in Alberta unlikely to be impacted by anthropogenic barium (Anderson 2004 *pers. com.*), ranged from: 10 to 219 µg/L in the Bow River basin (n=238); 7 to 389 µg/L in the Athabasca River basin (n=190); 31.6 to 506 µg/L in the North Saskatchewan River basin (n=95); 30 to 271 µg/L in the Oldman River basin (n=163) and 46 to 259 µg/L in the Red Deer River basin (n=62). The calculated average barium concentrations for each basin were 76 µg/L (Bow), 90 µg/L (Athabasca), 78 µg/L (North Saskatchewan), 110 µg/L (Oldman) and 100 µg/L (Red Deer). The combined average barium concentration for all basins was 91 µg/L.

Total metal concentrations in Saskatchewan surface waters were provided for samples collected from rivers, streams and lakes between 1998 and 2001 (Hase 2004 *pers. com.*). Samples were analysed by ICP-AES (Method 1728). In river and stream samples (n=68), barium concentrations ranged from 2 to 160 µg/L, with an overall average of 47 µg/L. In lake samples (n=103), barium ranged from 1 to 82 µg/L, with an overall average of 18 µg/L. Barium concentrations (total) measured in background surface waters (lakes and rivers) in rural Northern Manitoba (n=5) ranged from 4.6 µg/L to 8.7 µg/L (Yee 2004 *pers. com.*).

Barium emissions into water have also been reported during coal processing. The effluent from a coal conversion plant was reported to contain a barium concentration of 20 µg/L (Hildebrand *et al.* 1976).

A summary of concentrations in surface water is provided in Appendix 1. An average concentration of barium in Canadian surface waters was not determined for the purposes of setting human health based soil quality guidelines. Surface water used as a source for drinking water is addressed in the drinking water portion of this section.

2.5.6 Groundwater

Leaching and eroding of sedimentary rocks results in the natural release of barium into waters. This process is more significant with respect to groundwater than surface water (Kojola *et al.* 1978). Anthropogenic discharges into water occur during barium ore processing and subsequent industrial chemical processes involving barium (WHO 1990; ATSDR 1992).

Groundwater at a proposed coal mine site in B.C. was reported to contain barium concentrations of 1200 to 10 800 µg/L with a mean concentration of 7300 µg/L (Buchanan 1985).

Groundwater samples from the upper aquifer of the Scarborough Bluffs in the Toronto area contained a barium concentration of 90-302 µg/L whereas urban pore waters of the Don Valley contained 253-336 µg/L (Howard and Beck 1993). Barium variability was explained as the result of barium sulphate dissolving in response to lower sulphate concentrations in the pore waters during transport through the soil (Howard and Beck 1993).

Although not groundwater, landfill leachate is discussed to provide a contaminated sites context. Domestic landfill leachate collected from four locations situated around the western part of Lake

Ontario contained an average barium concentration of 109 µg/L (Howard and Beck 1993). Trace-metal analysis of urban groundwater was analysed by Howard and Beck (1993). Unpolluted evolving water samples and groundwater samples contaminated with road de-icing chemicals were collected from the Duffins Creek-Rouge River drainage basin (n=20). These samples contained barium in the range of 94-197 µg/L (unpolluted samples) and 54-128 µg/L (contaminated samples).

A summary of barium concentrations in groundwater is provided in Appendix 1. An average concentration of barium in Canadian groundwater was not determined for the purposes of setting human health based soil quality guidelines. Groundwater used as a source for drinking water is addressed in the drinking water portion of this section.

2.5.7 Drinking Water

The background barium concentration in Canadian drinking water is estimated to be 34.2 µg/L (arithmetic mean, SD=68.6, N=14 144) based on data obtained from the Ontario Ministry of Environment (1998-2007), Saskatchewan Ministry of Environment (2000-2009) and Department of Environment and Conservation, Government of Newfoundland and Labrador (2000-2009) (Health Canada 2011). Data from other provinces were not available to include in estimating the national background value. These data were used to develop the barium EDI values for exposure to drinking water used in the SQG calculation. The EDI methodology is further discussed in Section 5.2 of this document.

The mean barium concentration in Ontario treated drinking water is estimated to be 40.9 µg/L (SD=58.2, N=3695, range=3.97–786 µg/L) based on data from the Drinking Water Surveillance Program (DWSP) for years 1998 through to 2007 (OMOE 2010). Data were not available from the DWSP program for years beyond 2007.

The mean barium concentration in Saskatchewan drinking water is estimated to be 47.1 µg/L (SD=80.6, N=2517, range=0.25–960 µg/L) based on data from Government of Saskatchewan's (GS) Ministry of Saskatchewan Environment (MSE) for years 2000 through 2009 (GS 2008).

The mean barium concentration in Newfoundland and Labrador drinking water is estimated to be 27.0 µg/L (SD=68.0, N=7932, range=0–1150 µg/L) based on data from the Government of Newfoundland and Labrador (GNL), Water Resources Management Division for tap water samples taken at public water supplies from January 2000 to June 2009 (GNL 2009).

A summary of barium concentrations in drinking water is provided in Appendix 1.

2.5.8 Sediments

Baseline sediment barium concentrations in Durham Region, Ontario were reported to be 78.59 mg/kg (baseline concentration represents maximum, upper confidence limit of the mean or the detection limit) (Jacques Whitford 2009).

A Yukon-wide median sediment concentration of 814 mg/kg was reported from 25 739 samples. Median barium concentrations reported for each geological province were as follows: Cassiar Platform (820 mg/kg, n=2306), Insular (538 mg/kg, n=399), Intermontane (920 mg/kg, n=2324),

North-American Shelf (620 mg/kg, n=4732), Northern Shelf (600 mg/kg, n=937), Selwyn Basin (920 mg/kg, n=4619), Triass-Cretac (465 mg/kg, n=1837) and Tanana Terrane (870 mg/kg, n=7472) (Heon 2003).

Loring (1979) used atomic absorption spectrometry to determine total barium concentrations in 83 samples of bottom sediments taken from various regions of the Bay of Fundy (New Brunswick and Nova Scotia). Concentrations ranged from 150 to 540 mg/kg with an average of 310 mg/kg. Generally higher concentrations of barium were associated with fine grained sediments (400 mg/kg) than with coarse grained sediments such as sand (290-300 mg/kg).

About 10% of the muds used in offshore drilling operations can be lost and may result in barium pollution, especially in coastal sediments (Ng and Patterson 1982)

A summary of barium concentrations in sediments is provided in Appendix 1. An average concentration of barium in Canadian sediments was not determined for the purposes of setting human health based soil quality guidelines.

2.5.9 Biota Used as Human Food

In rural gardens in Northern Manitoba, barium concentrations (dry weight) were reported for radishes (18.2 mg/kg), potatoes (0.58 mg/kg), carrots (22.2 mg/kg), turnips (17 mg/kg), strawberries (11.8 mg/kg), blueberries (11.4 mg/kg) and mossberries (7.15 mg/kg) (Yee 2004 *pers. com.*). It should be noted that these concentrations were determined on a dry weight basis and are thus different than those determined (on a wet weight basis) in Health Canada's Total Diet Study which is discussed in the next section (2.5.10).

Lobel *et al.* (1991) reported barium levels in mussels (*Mytilus edulis*) (n=10) collected from a relatively pristine lagoon at Bellevue, Newfoundland. The lowest value was reported for the foot (0.0979 mg/kg dry wt) and the highest for the digestive gland (7.9 mg/kg dry wt). The kidney contained a barium concentration of 1.1 mg/kg dry wt, whereas the gills and mantle contained 0.14 and 0.38 mg/kg dry wt, respectively.

A summary of available concentrations in biota used as human food is provided in Appendix 1. Barium concentrations in biota used as food are included in the dataset used to generate the estimated daily intake of barium resulting from food ingestion as discussed in the next section.

2.5.10 Commercial Foods

Health Canada's Food Directorate has provided estimated daily intakes of barium from food in Canadians from the Health Canada Total Diet Study (HC TDS) (Dabeka *et al.* 2010). Intake rates were provided for various age groups from 2000 to 2007 (inclusive) as presented in the table below. These data were considered to be the most appropriate data to represent the Canadian population since they were developed recently by Health Canada in a methodical manner and have therefore been used to develop the barium EDI values for exposure to food used in the SQG calculation. The EDI methodology is further discussed in Section 5.2 of this document (Health

Canada 2011). The details regarding barium intake through food ingestion is presented in Table 2 below and in Appendix 2.

Table 2. Barium Intake via food ingestion by age group 2000-2007

Barium concentration ($\mu\text{g}/\text{kg}\cdot\text{d}$)	0-6	7mo-4yrs	5-11yrs	12-19yrs	20+yrs
	months	years	years	years	years
	M & F	M & F	M & F	M & F	M & F
arithmetic mean	19	21	16	9.1	7.0
standard deviation	3.0	2.5	1.8	1.1	1.1

A summary of barium intake via food ingestion for additional sources (including international data) included in previous guidelines is presented in Appendix 1. Exposure to barium in the diet has been noted to be highly variable because of varying amounts of barium in different foods. Nuts such as pecans and Brazil nuts have been reported to be high in barium (Dallas and Williams 2001). Dallas and Williams (2001) highlight a study by Lisk *et al.* (1988) which documents 179.2 mg of barium in 92 g of Brazil nuts (1948 mg/kg).

2.5.11 Human Breast Milk

In estimating the average concentration of barium in Canadian human breast milk, studies from other developed countries were considered due to limited Canadian data. Based on one Canadian study (Friel *et al.* 1999), two Austrian studies (Krachler *et al.* 1998, Krachler *et al.* 1999), two Italian studies (Coni *et al.* 1990, Coni *et al.* 2000) and an Emirati study (Abdulrazzaq *et al.* 2008), the average barium concentration in human breast milk was estimated to be 3.61 $\mu\text{g}/\text{L}$ (arithmetic mean, $\text{SD}=8.67$, $\text{N}=495$) (Health Canada 2011). This concentration includes breastmilk at various stages/maturity). These data were used to develop the barium EDI values for exposure to breast milk used in the SQG calculation (applicable to breastfed infants only). The EDI methodology is further discussed in Section 5.2 of this document.

For the one Canadian study (Friel *et al.* 1999), only the medians are reported. If it is assumed that the medians equal the mean values, then in comparison to other studies, the average of the values in Canadian women are slightly lower than the average of the values reported by other non-Canadian studies and the median values fall within the range of values reported by other non-Canadian studies (Health Canada 2011).

2.5.12 Consumer Products

Barium has been found to be present in tobacco and tobacco products. Oladipo *et al.* (1993) reported a barium concentration range of 45.2 to 385 mg/kg in Nigerian tobacco and 81.3 to 144 mg/kg in Nigerian cigarettes. The mean barium concentration in Egyptian cigarettes is reported to be 69.4 mg/kg and in Turkish tobacco is reported to be 52 mg/kg. Hildemann *et al.* (1991) did not detect barium in cigarette smoke. Data regarding barium levels in Canadian cigarettes smoke were not available (Kaiserman 1991).

Taylor *et al.* (2003) reported a mean concentration in wine of 140 µg/L (SD=100, n = 59) for the Okanagan Valley and 115 µg/L (SD=57, n=36) for the Niagara Peninsula.

Pyrotechnics and fireworks release aerosol barium that results from the use of barium nitrate as a combined pyrotechnic oxidiser and coloring agent (Steinhauser *et al.* 2008). Barium compounds released by pyrotechnics include: BaO, Ba(OH)₂, BaCl₂ as well as unburnt Ba(NO₃)₂, all of which are water soluble. Steinhauser *et al.* (2008) reported fireworks caused an increase in the barium concentration in snow by a factor of 6 to 580 (0.042-3.4 mg/kg) compared to the blank value (0.0044 mg/kg).

Barium sulphate has been used in cosmetic products because of its stability (Sneyers *et al.* 2009) who found barium concentrations of 15.4 to 256 mg/kg in lipstick, 74 to 748 mg/kg in eye shadow, and 0.049 mg/kg in cream samples. Barium concentrations in soap samples from the Asian market were found to contain 3 to 30 mg/kg barium and bronzing powders were found to contain 150 to 230 mg/kg barium (Sneyers *et al.* 2009).

2.5.13 Rain, Snow and Fog

In Ontario, barium in precipitation was 1.45 to 3.0 µg/L with a mean of 2.3 µg/L (Wagner 1991 *pers. com.*).

A summary of available environmental concentrations in rain, snow and fog is provided in Appendix 1 (international). An average concentration of barium in Canadian rain, snow and fog was not determined for the purposes of setting human health based soil quality guidelines.

2.6 Existing Criteria and Guidelines

The existing federal and provincial Canadian guidelines, standards and criteria for barium in soil, groundwater and drinking water are presented in Table 3 below.

Table 3. Existing criteria and guidelines for barium in Canadian jurisdictions

Jurisdiction	Category	Criterion/Guideline	Reference
Ontario	Full Depth Generic Site Conditions Standards. Potable and non-potable groundwater situations for both coarse and medium/fine textured soils. Agricultural/Other Residential/Parkland/Institutional Industrial/Commercial/Community Stratified Site Condition Standards (potable and non-potable groundwater) • Surface Soil (both coarse and medium/fine textured soils). Residential/Parkland/Institutional Industrial/Commercial/Community • Subsurface soil Residential/Parkland/Institutional Industrial/Commercial/Community Potable Groundwater Criteria (all land uses) Non-potable Groundwater Criteria (all land uses)	390 mg/kg ¹ 390 mg/kg 670 mg/kg 390 mg/kg 670 mg/kg (8600) 7700 mg/kg ² (8600) 7700 mg/kg ² 1000 µg/L 29 000 µg/L	OMOE 2009.
Quebec	Generic Criteria for Soils A (Background levels for metals and quantification limits for organics) B (Maximum acceptable limit for residential, recreational, institutional and commercial (in residential area) land uses)) C (Maximum acceptable limit for commercial (in non-residential areas) and industrial land uses)) Groundwater SW DW	200 mg/kg 500 mg/kg 2000 mg/kg 5300 µg/L 1000 µg/L	MEF 1998.
Yukon	Generic Numerical Soil Standards (Schedule 1) Agricultural Parkland/Residential Commercial/Industrial Generic Numerical Water Standards FAQL MAQL DW	750 mg/kg 500 mg/kg 2000 mg/kg 10 000 µg/L 5000 µg/L 1000 µg/L	Yukon Government, 2002.
Alberta	Guidelines for Barite Soil Remediation Agricultural Residential/Parkland Commercial Industrial Guidelines for Extractible Barium from Barite Sites Agricultural Residential/Parkland Commercial and Industrial Guidelines for Barium for Non-Barite Sites Agricultural Residential/Parkland Commercial and Industrial	10 000 mg/kg 10 000 mg/kg 15 000 mg/kg 140 000 mg/kg 250 mg/kg 250 mg/kg 450 mg/kg 750 mg/kg 500 mg/kg 2000 mg/kg	AENV 2010; AENV 2009a.
British Columbia	Generic Numerical Water Standards FAQL MAQL DW	10 000 µg/L 5000 µg/L 1000 µg/L	BCMVLAP 2009.
Canada	Soil Quality Guidelines (non-barite site) ³ Agricultural Residential/Parkland Industrial/Commercial Canadian Environmental Quality Guidelines ¹ and Guidelines for Canadian Drinking Water Quality ² DW	750 mg/kg 500 mg/kg 2000 mg/kg 1000 µg/L	CCME 1999. CCME 1999, HWC 1990.

¹ Guideline value is not provided for agricultural land use under non-potable groundwater scenario.

² Bracketed value applies to medium/fine textured soil, unbracketed value applies to coarse soil.

³ Adopted by the NWT, British Columbia, Alberta, Saskatchewan, Manitoba, New Brunswick, Nova Scotia, PEI, Newfoundland & Labrador.

⁴ Criterion or guideline used by all provinces and territories

A: background concentrations, B: moderate soil contamination (requires additional study), C: threshold value (requires immediate cleanup)

FAQL: freshwater aquatic life, MAQL: marine (and/or estuarine) aquatic life

DW: groundwater used as drinking water; SW: groundwater seeping into surface water or infiltrating sewers

3. ENVIRONMENTAL FATE AND BEHAVIOUR

Current release estimates for barium were not identified for Canada; however, 1998 release estimates for barium compounds from American manufacturing and processing facilities were 900 tonnes to air, 45 tonnes to water and 9300 tonnes to soil (CICAD 2001).

3.1 Atmosphere

In air, barium is associated with dust and suspended particulates. Barium occurs mainly as the sulphate or carbonate form and possibly as other insoluble forms (WHO 1990; ATSDR 1992). Data from the National Air Pollution Surveillance Program suggest that much of the barium in ambient air is bound to the coarse fraction of particulate matter (2.5 to 10 µm) (CCME 1999).

Depending on the particle size the residence time of barium in the atmosphere may be several days with larger particles settling out more quickly (CICAD 2001) Particulates are likely removed from the atmosphere by wet and dry deposition (HSDB 2003).

3.2 Water

Barium concentrations in water are determined by the solubility of barium salts and the adsorption of barium on active surfaces. Soluble barium compounds are mobile in the environment and have been detected in surface water, groundwater, drinking water and sediment (HSDB 2003). Aqueous environments containing chloride, nitrate and carbonate anions will increase the solubility of barium sulphate and at pH less than or equal to 9.3, the Ba(II) ion will be the dominant barium species and will be controlled by the sulphate ion concentration (ATSDR 2007). Natural (i.e. surface water) and treated (i.e. drinking water from treatment plant) waters generally contain sulphate at a level which limits the barium ion concentration to <1500 mg/L (ATSDR 2007).

At pH levels greater than 9.3, barium carbonate becomes the dominant species and limits Ba (II) solubility (ATSDR 2007; Bodek *et al.* 1988). The barium concentration in waters has been reported to be related to the water hardness, defined as the sum of the polyvalent cations present, including calcium, magnesium, iron, manganese, copper, barium and zinc ions (NAS 1977).

Barium is capable of adsorption onto clays, manganese oxides, zeolite minerals and is found to occur in deep-sea manganese nodules and freshwater manganese deposits. Ferromanganese nodules found on the ocean floor are reported to be one of the major barium sinks (Adriano 1986). The increase in barium concentrations in the marine environment with increased depth may be due to the incorporation of barium into organisms in the euphotic zone which undergo sedimentation and release into deeper waters (CICAD 2001). According to Schroeder *et al.* (1972), argillaceous (fine grained, clay-like) sediments have a preferential absorption of barium salts in sea water.

Unless removed by precipitation, adsorption or other processes, barium in fresh surface water ultimately reaches the oceans and combines with the sulphate ions forming barium sulphate (CICAD 2001). Since sulphate ions are in a relatively higher concentration in sea water, only 0.006% of the soluble barium brought in by fresh waters remains in solution (CICAD 2001). In the upper layers of the ocean, barium is depleted through incorporation into biological matter and

adsorption onto suspended particles. Adsorbed barium is released upon the destruction of particulate matter in transit to the ocean floors resulting in higher concentrations in deep water (WHO 1990). A steady state relationship occurs in oceans balancing input and sedimentation to the ocean floor (Wolgemuth and Brocker 1970). In 1970, Wolgemuth and Brocker determined the barium concentration in the Atlantic and Pacific Oceans. The results showed a range of 8 µg/L (surface water) to 14 µg/L (deep water) for the Atlantic Ocean and a range of 8 µg/L (surface water) to 31 µg/L (deep water) for the Pacific Ocean.

In 1972, Schroeder *et al.* reported a median concentration of 43 µg/L barium (range 1.7-380 µg/L) in municipal waters of the United States.

3.3 Sediment

The soil water distribution coefficients (K_d) for sediments have been estimated to range from 200 to 2800 (DOE 1984; Rai *et al.* 1984).

Barium in sediment occurs predominantly as barite. Under anaerobic conditions, barites can be reduced through bacterial activity, to sulphides that then react with iron releasing barium (AENV 2009a). Barium-rich areas of black siliceous ooze or clay occur in sediment and are preserved as interbedded barites and black shales.

3.4 Soil

There are soluble, insoluble, inorganic and organic forms of barium present in soil. Barium occurs naturally in soils with high levels associated with limestone, feldspar and shale deposits (WHO 1990). Weathered, soluble barium minerals in solution may come in contact with sulphate solutions resulting in barium depositing in geological faults as BaSO₄. However, if insufficient sulphate is present, the soil material formed will be partially saturated with barium where it may displace other cations in the soil (WHO 1990). Not all barium in soil is readily available to living organisms.

Barium mobility in soils depends on soil characteristics and the solubility of the barium compounds formed (ATSDR 2007; CICAD 2001). Barium is easily precipitated as sulphates and carbonates. Barium reacts readily with metal oxides and hydroxides, being subsequently adsorbed onto soil particles (Rai *et al.* 1984). Barium will displace other adsorbed alkaline earth metals from MnO₂, SiO₂ and TiO₂ (Rai *et al.* 1984) as well as substituting for potassium (I) (Adriano 1986). In addition, adsorption occurs through electrostatic interactions controlled by the ability of the sorbent to exchange cations (WHO 1990). Barium is strongly adsorbed to clay minerals and organic and fine structured soils (WHO 1990; ATSDR 2007). Generally, barium shows limited mobility because of the formation of water insoluble salts and the inability of barium to form soluble humic and fulvic complexes (WHO 1990). However, barium may move into groundwater under acidic conditions since the solubility of barium compounds increases with decreasing pH (ATSDR 2007; CICAD 2001). It is noteworthy that application of lime or sulphur to soil tends to immobilise barium by forming the sparingly soluble BaCO₃ and BaSO₄ (Adriano 1986). Additionally, under the following circumstances the solubility of insoluble barium compounds (i.e. barite) may be increased: an anaerobic environment with reduced reduction-oxidation potential, elevated chloride

or dissolved salt concentrations and low sulphate concentration (US EPA 1991; Branch *et al.* 1990).

Barite is highly insoluble; therefore, barium within barite (BaSO_4) will not necessarily be released to the environment (AENV 2009a). As previously discussed, Alberta Environment (AENV) and the British Columbia Ministry of Environmental (BCME) have developed barite guidelines to be used only at barite contaminated sites (AENV 2009a; BCME 2009). Although risk assessment professionals completing site-specific assessments may calculate alternate values that consider the unique attributes of individual sites being evaluated, employment of such factors in the development of SQG were not considered appropriate at the current time and instead, a conservative approach was used that is intended to be protective of all possible situations.

As discussed in section 2.3, barite is commonly used in the oil and gas industry in drilling mud. Bates (1988) studied the management of drilling waste (reserve pit fluids and sludges) by land farming, and the fate and potential environmental effects of the pollutants present in the fluids. The results showed that barium can leach through soil containing drilling waste mud during the land farming process. It should be noted that the amount leached was very small in comparison to the total loading of the soil, 0.22 to 1% of the total barium load leached through the experimental soil column (Bates 1988). The leaching is likely due to the presence of chloride in the pit fluids and soil resulting in formation of chloride complexes (i.e. barium chloride) which are highly soluble compared to other barium compounds (Bates 1988).

3.5 Indoor Dust

Rasmussen *et al.* (2008) reported that indoor dust and soil are geochemically distinct. Indoor dust has approximately five times the organic matter as soil samples (Rasmussen *et al.* 2008). Organic carbon is a key factor controlling metal partitioning and bioavailability. The higher metals concentration in indoor dust compared to soils may be explained by the affinity some metals have for organic matter, in addition to the smaller particle size of dust (Rasmussen *et al.* 2008). Consequently, the use of outdoor soil metals data to predict indoor dust concentrations may result in the underestimation of indoor dust exposures (Rasmussen 2004). In areas where spatial correlations do exist between indoor dust and exterior soil concentrations, the correlations suggest an elevated external source (i.e. mining or other sources of industrial contamination) (Rasmussen *et al.* 2004).

3.6 Biota

The ATSDR (2007) indicates that the magnitude of bioconcentration in plants and terrestrial animals from barium in soil is not well characterised. Further research is needed in the area of bioaccumulation from soil and biomagnification within terrestrial and aquatic food chains to better understand potential human exposure to barium through the ingestion of biota (ATSDR 2007). For the purpose of calculating the Soil Quality Guideline for the Protection of Human Health, barium was considered to not bioaccumulate. This is consistent with the US EPA Region 5 Superfund (2008) Ecological Toxicity Information which states that barium does not bioaccumulate and concentrations in higher species rarely exceed 10 mg/kg. Some specific studies regarding barium bioaccumulation are discussed below.

Barium is found in most plants, although not reported to be an essential element (WHO 1990). The concentration depends on the soil and the plant species. Although not thoroughly studied (ATSDR 2007), barium bioconcentration in land plants is low relative to the concentration of barium in soils (Schroeder 1970; WHO 1990) and no plant uptake of barium from air has been reported (WHO 1990). It is actively and strongly accumulated by legumes, grain stalks, forage plants, trees (red ash, black walnut, hickory, Brazil nut and Douglas fir) and plants of the genus *Astragalus* (Reeves 1986; WHO 1990; CICAD 2001). Except for the Brazil nut, the parts of the plant that accumulate barium are rarely eaten by humans (WHO 1990). The distribution of barium in plant tissues indicates that highest levels are found in the roots. In sedge and nutgrass, 97.6 and 131.9 mg/kg was reported in the roots, 15.4 and 37.5 mg/kg in the leaves, 10.0 and 11.6 mg/kg in the seeds and 9.2 and 11.1 mg/kg in the stem (Cherry and Guthrie 1979).

Tree foliage sampling data (dry weight basis) was available for background locations in Ontario and Manitoba. In Ontario, barium was detected in the foliage of silver maple trees (n=63) in rural locations (Essex and Kent counties) at concentrations ranging from 2.4 to 9.5 mg/kg (dry weight) (Gizyn 2002). By comparison, in rural northern Manitoba, background barium concentrations in coniferous trees (n=3) ranged from 67 to 160 mg/kg (dry weight) (Yee 2004 *pers. com.*).

A barium bioconcentration factors (BCFs) study reported a soil to plant BCF of 0.4 based on exposure of a variety of plant species to mean barium soil concentrations of 104 mg/kg. BCFs of 0.2 (terrestrial insects) and 0.02 (white-footed mouse and hispid cotton rats) were reported for barium under the same soil exposure conditions (CICAD 2001).

Under experimental conditions, bush beans and barley displayed toxicity and accumulated a barium concentration of 22 200 mg/kg (bush bean leaves) and 9770 mg/kg (barley shoot leaves) when grown in soil (loam) spiked with 2000 mg/kg barium nitrate (Chaudry *et al.* 1977). In contrast, no difference in barium uptake was found in swiss chard and ryegrass plants growing in soils amended with two types of drilling fluid preparations when compared to controls (Nelson *et al.* 1984).

The possibility of the accumulation of barium by the aquatic freshwater plant *Pontedaria cordata* (pickerelweed) has been suggested. Cowgill (1973) reported a barium concentration of 48 mg/kg in the leaves of this plant growing in Linsley Pond, Connecticut.

Barium has been found in hard and soft parts of marine plants, animals and bacteria, including algae, diatoms, plankton and molluscs. Bioconcentration has been reported to occur by a factor of 1000 (marine plants), 260 (brown algae), 120 (plankton) and 100 (marine animals) times the level present in water (Bowen 1979; Schroeder 1970). Relatively high barium concentrations have been reported in some Canadian marine fish and shellfish (see Appendix 1).

A bioconcentration factor of 129 L/kg was estimated for freshwater fish based on dissolved barium concentrations in surface water of 0.07 mg/L and whole-body barium concentrations of 2.1 mg/kg in fish (CICAD 2001). Bioaccumulation of barium has also been found in clams and minnows in freshwater ecosystems. In studies of Tadenac Lake, Ontario, barium was concentrated in the soft tissue of the filter-feeding clam at 9 to 446 mg/kg (mean 108 mg/kg as wet wt) and in the muscle tissue of the benthic detritus-feeding bluntnose minnow at 4.4 to 9.8 mg/kg (mean 8.0 mg/kg as wet

wt) (Wren *et al.* 1983). Barium levels were reported to be less than the detection limit of 0.4 mg/kg in rainbow smelt, smallmouth bass, northern pike and lake char.

Barium concentrations (wet weight) in muscle tissue from birds and mammals were: common loon 0.6 mg/kg; American coot 0.6 mg/kg; herring gull 0.4 mg/kg (0.3-0.6); beaver 0.5 mg/kg (0.4-0.7); racoon 0.3 mg/kg (0.2-0.4); and otter 0.7 mg/kg (0.5-0.9) (Wren *et al.* 1983).

4.0 BEHAVIOUR AND EFFECTS IN HUMANS AND NON-HUMAN MAMMALIAN SPECIES

4.1 Overview

The behaviour and effects of barium in humans and mammalian species have been reviewed by several international health agencies including the Agency for Toxic Substances and Disease Registry (ATSDR 2007), US Environmental Protection Agency (US EPA 2005; 1998), World Health Organisation (CICAD 2001), and Health Canada (HWC 1990). It is not the role or the intention of this document to comprehensively re-evaluate the toxicology of barium. Such reviews have been carried out by agencies responsible for protecting human health in Canada and other jurisdictions, as noted above. This report focuses on the studies most relevant to the toxicity reference values (TRVs) for barium, for use in development of SQGs for the protection of human health.

As discussed in Section 2.4, barium may be found in a variety of chemical forms including:

- barium sulphate
- barium carbonate
- barium chloride
- barium hydroxide

The majority of the toxicity data for barium is based on studies using soluble forms of barium, although the most predominant form of barium found in the environment is insoluble barium sulphate (barite), which is not considered in this SQG.

The lack of data available regarding the carcinogenicity of barium has resulted in it being classified in group VA (inadequate data for classification) by Health Canada (HWC 1990). A similar classification (Class D) was adopted for barium by US EPA (1998) under EPA's *Guidelines for Carcinogen Risk Assessment* (US EPA 1986). Under the *Proposed Guidelines for Carcinogen Risk Assessment* (US EPA 1996), barium is considered not likely to be carcinogenic to humans following oral exposure as adequate chronic oral exposure studies in rats and mice have not demonstrated carcinogenic effects. Due to the lack of inhalation exposure data, the carcinogenicity of inhaled barium cannot be assessed (US EPA 1998). The International Agency for Research on Cancer (IARC) and other organisations have not classified barium with regards to carcinogenicity. Barium is therefore treated as a threshold toxicant for the development of human health soil quality guidelines.

4.2 Mode of Toxicity

The toxicity of barium is attributed to the barium ion (Ba^{+2}) and therefore, the toxicity of a particular barium compound is related to that compound's solubility (ATSDR 2007; US EPA 2005; CICAD 2001). Barium ions are readily absorbed from the gastrointestinal tract and lung. The intestinal mucosa of mammals is highly permeable to barium ions and is involved in the rapid movement of soluble barium salts into the blood (DiBello *et al.* 1991).

The mechanism of barium toxicity is related to its ability to substitute for calcium. Toxicity results from stimulation of smooth muscles of the gastrointestinal tract, the cardiac muscle, and the voluntary muscles, resulting in paralysis (DiBello *et al.* 1991). Toxicity can also be attributed to the physiological antagonist of barium ions to potassium ions, which possess a similar effective ionic radius. Hypokalemia, a key feature of barium toxicity, is associated with the ability of barium ions to block potassium channels (Koch *et al.* 2003).

4.3 Toxicokinetics

4.3.1 Absorption

A wide range of absorption rates have been reported in the scientific literature for barium with oral values ranging from less than 1% to greater than 80% in animal studies. The degree of absorption of barium from the gastrointestinal tract depends on the solubility of the compound, the animal species, contents of the gastrointestinal tract, diet and age. Soluble barium salts are absorbed most readily. Data from studies in rats and man indicate that insoluble barium compounds may also be absorbed to a significant extent (Clavel *et al.* 1987; McCauley and Washington 1983).

Less than 10% of ingested barium is believed to be absorbed in adults; however, absorption may be significantly higher in children (WHO 1990). Taylor *et al.* (1962) reported gastrointestinal absorption following a single gavage dose of radiolabeled barium chloride in rats. Gastrointestinal absorption of barium was approximately 7–8% in older (6–70 wk) nonfasted rats, 20% in older fasted rats and 63–84% in younger (14–22 d) nonfasted rats. While these data suggest that both age and feeding status may affect barium absorption, absorption was measured only 7 hours after administration of the barium; therefore suggesting the study may have been terminated prior to completion of absorption (US EPA 1998).

Shock *et al.* (2007) investigated the bioaccessibility of barium from different soil and dust sources. The amount of barium available for absorption varied greatly, between 0.07 and 66%, depending on sample location, grain size and the solid-to-fluid ratios used in the *in vitro* experiments. The bioaccessibility of barium in tundra soils was higher than in dust samples from barite-rich mine waste rock and gyro crusher ore dust. This was thought to be due to the presence of more soluble forms of barium in the tundra soil. Bioaccessibility was also affected by the analytical method chosen to detect barium concentrations.

For consideration in human health risk assessments, a relative oral absorption factor of 100% was selected for barium, which provides needed conservatism due to the wide range of absorption rates

reported. This assumption may overestimate barium absorption when used to estimate risk at contaminated sites as it assumes that all barium exists in a bioavailable form.

Limited data are available on barium absorption from the respiratory tract. Animal data reviewed by the ATSDR (2007) and US EPA (1998) indicate that barium compounds are absorbed across the respiratory tract (including barium compounds that have low water solubility). Differences in water solubility may account for differences in clearance rates of barium from the respiratory tract. Particle size and the rate of clearance from the upper respiratory may also influence absorption. No data are available on the absorption of inhaled barium compounds in humans.

No data are available on the dermal absorption of barium compounds in humans. One animal study reviewed by the ATSDR (2007) showed that barium applied to the skin of piglets was found in various layers of skin (Shvydko *et al.* 1971 as cited in ATSDR 2007).

4.3.2 Distribution

Absorbed barium is rapidly distributed in the bloodstream and is deposited principally in bone (CICAD 2001; US EPA 1998; NAS 1977). Uptake of barium into bones is rapid. One day after inhalation exposure to barium chloride aerosol, 78% of the total barium body burden was found in the skeleton of exposed rats. After eleven days, more than 95% of the total barium body burden was found in the skeleton (Cuddihy *et al.* 1974).

The whole body content of barium in humans is approximately 22 mg, of which 93% is found in the bone and connective tissues, with smaller amounts being present in the fat, skin and lungs (Schroeder *et al.* 1972). The presence of barium in infant and stillborn foetal tissues indicates that barium also crosses the placental barrier in humans (Schroeder *et al.* 1972).

McCauley and Washington (1983) reported that barium levels in the heart, eye, skeletal muscle and kidneys were higher than levels in whole-blood following oral administration of radiolabeled barium chloride in dogs. High concentrations of barium have also been reported in the eye, particularly in the pigmented structures (Reeves 1986).

No data are available regarding the distribution of barium following dermal exposure.

4.3.3 Metabolism

Barium and barium compounds are not metabolised in the body but may be transported and incorporated into tissues (ATSDR 2007).

4.3.4 Elimination

The principal route of excretion of barium in humans and animals is faecal, although barium is also eliminated in the urine (ATSDR 2007; US EPA 1998; Ohanian and Lappenbusch 1983). Schroeder *et al.* (1972) reported that, for a typical daily intake of 1.3 mg/person/day, approximately 90% of the barium is excreted in the faeces and 2% in the urine. Tipton *et al.* (1969) found similar results in a study of two men, where 95–98% and 2–5% of the daily barium intake was excreted in the

faeces and urine, respectively. The biological half-life of barium is relatively short. The NAS (1977) reported that 20% is excreted in the faeces and 7% is excreted in the urine within 24 hours.

No data are available regarding the elimination of barium following inhalation or dermal exposure in humans.

4.3.5 Concentrations in Human Tissues and Biological Fluids

The total body burden of barium in a 70 kg adult man is estimated to be 22 mg (Tipton *et al.* 1963; Schroeder *et al.* 1972; ICRP 1974) with the majority (93%) concentrated in bone and connective tissue (Schroeder 1970; NAS 1977). Mean bone levels ranging from 7 to 8.5 mg/kg were reported by Sowden and Stitch (1957), whereas Schroeder *et al.* (1972) estimated levels to be 2 mg/kg in the skeleton. According to Schroeder *et al.* (1972) barium tends to accumulate in or to be lost from some tissues with age. The deposition of barium in bone is similar to that of calcium; however, the process for barium occurs faster and is not reversible (Venugopal and Luckey 1978). The majority of the barium in blood is reported to be present in the plasma fraction (Schroeder *et al.* 1972).

Absorbed barium has been identified in the following human soft tissues: adrenal glands, aorta, thyroid, lung, muscle, testes, ovary, uterus and urinary bladder (Venugopal and Luckey 1978). A U.S. study, identified barium concentrations in the following soft tissues: pancreas (1.5 mg/kg in ash); kidney (1.2 mg/kg in ash); brain (<0.2 mg/kg in ash); liver (<0.2 mg/kg in ash); aorta (7 mg/kg in ash); spleen (0.5 mg/kg in ash); heart (0.7 mg/kg in ash); testi (1.0 mg/kg in ash); and lung (13 mg/kg in ash) (Tipton *et al.* 1965). Barium concentrations in these tissues from African, East Mediterranean and South East Asian subjects were found to be higher and distributed differently (Tipton *et al.* 1965).

Pathological conditions can alter the barium concentration in human hair and blood. Ward and Bryce-Smith (1985) reported a statistically significant increase in the concentration of barium in the hair and blood of patients with multiple sclerosis (3.37 ± 2.92 mg/kg and 144 ± 19 µg/L, respectively) when compared with control concentrations (1.68 ± 0.713 mg/kg and 126 ± 22 µg/L, respectively).

Exposure to higher barium levels in the environment can also increase barium uptake. Curzon *et al.* (1984) found an increased barium concentration relative to calcium in primary teeth from children who drank water containing barium concentrations greater than 10 000 µg/L compared to control children whose water supply contained <100 µg/L (28.3 vs 10.4 µg barium/g calcium). Similarly, Miller *et al.* (1985) reported that the ratio of barium to calcium was five times higher in the teeth of 34 children exposed to drinking water containing high concentrations of barium (10 000 µg/L) than that of 35 children from another community exposed to lower barium levels (200 µg/L). The two communities were similar with respect to population, ethnic composition and socioeconomic status.

Data regarding barium concentrations in human tissues and fluids is summarised in Appendix 1.

4.4 Acute Toxicity

Data on the acute toxicity of barium is largely limited to case reports involving oral exposure to soluble barium compounds. The intentional or accidental ingestion of soluble barium compounds can result in acute barium toxicity. Systemic effects of barium toxicity include gastrointestinal effects such as abdominal pain, nausea, vomiting and diarrhea, hypokalemia which can result in hypertension, cardiac arrhythmias, and muscle paralysis, and kidney damage (ATSDR 2007; US EPA 2005; Jourdan 2001; Koch *et al.* 2003; Stockinger 1981). Depending on the dose and solubility of the barium salt, death may occur in a few hours or days (Stockinger 1981).

The acute lethal oral dose of barium chloride for humans has been estimated to be between 3 and 4 g; the acute toxic dose is 0.2 to 0.5 g (Reeves 1986). Repeated exposures to barium chloride in table salt are believed to have caused recurrent outbreaks of "Pa-Ping" disease (a transient paralysis resembling familial periodic paralysis) in the Szechwan province of China (Shankle and Keane 1988).

4.5 Sub-Chronic and Chronic Systemic Toxicity

4.5.1 Oral Exposure

Several investigators have examined the effects of oral exposure to barium, particularly on the cardiovascular system. In general, these studies have not found significant alterations in blood pressure or ECG readings. One study, (Perry *et al.* 1989) did find significant increases in blood pressure in rats orally exposed to barium, although these effects were not seen in other studies involving exposure to higher doses of barium (McCauley *et al.* 1985; NTP 1994). Results of animal studies indicate that the most sensitive effect of oral exposure to barium is renal toxicity (ATSDR 2007; US EPA 1998).

A study by Schroeder and Mitchener (1975a) of Long-Evans rats exposed for their lifetime to 5 ppm barium as barium acetate in drinking water (equivalent to 0.61 mg/kg bw/day for males and 0.67 mg/kg bw/day for females), revealed a slight increase in growth rates of females and a significant increase in proteinuria in males. No effects were observed for serum levels of cholesterol, glucose or uric acids, or incidence of tumours upon gross examination at autopsy. It should be noted that mortality in this study was approximately 35% in males and 22% in females due to an epidemic of pneumonia; there were 52 animals of each sex per group at the initiation of the study. In a similar study by Schroeder and Mitchener (1975b), white Swiss mice of the Charles River CD strain were exposed over their lifespan to 5 ppm barium acetate in drinking water (equivalent to 1.18 mg/kg bw/day for males and 1.20 mg/kg bw/day for females), resulting in a significant reduction in the survival of males but no effects on body weight gain, oedema, blanching of incisor teeth or incidence of tumours based upon gross examination at autopsy.

Tardiff *et al.* (1980) exposed male and female Charles River rats to barium as barium chloride at concentrations of 10, 50 and 250 mg/L (evaluated as 1.7, 8.1 and 38.1 mg/kg bw/d for males and 2.1, 9.7 and 45.7 mg/kg bw/d for females) in drinking water for 13 weeks with interim sacrifices at four and eight weeks.

No adverse biochemical, haematological or histological effects were observed. There were also no effects on food consumption or body weight gain. Water consumption was slightly depressed in the highest dose group (38.1 to 45.7 mg/kg bw/day). A slight decrease in adrenal weights was reported in some dose groups, but did not appear to be dose-related.

Perry *et al.* (1989; 1983) studied the effect of the ingestion of barium in drinking water on blood pressure in rats. Groups of female Long-Evans rats were exposed to 1, 10 or 100 ppm barium chloride in drinking water (equivalent to 0.051, 0.51 and 5.1 mg/kg bw/day respectively) for up to 16 months. In rats receiving 100 ppm barium (5.1 mg/kg bw/day), there were significant and persistent increases in mean systolic blood pressure (12 mmHg) after 1 month, which gradually increased to a mean of 16 mmHg after 16 months of exposure. Rats exposed to 100 ppm also had depressed rates of cardiac contraction and electrical excitability, and reduced ATP and phosphorylation potential at 16 months. At 10 ppm barium (0.51 mg/kg bw/day), there were mean increases in blood pressure of 4 to 7 mmHg by 8 months, which persisted thereafter. There were no changes in mean systolic blood pressure in animals exposed to 1 ppm barium (0.051 mg/kg bw/day). It has been suggested that the low mineral content of the diet in this study may have influenced the results (ATSDR 2007).

A series of studies by McCauley *et al.* (1985) examined the effects of barium chloride in drinking water on blood pressure, electrocardiograms and histology in rats. No barium related changes in blood pressure were seen in groups of Sprague-Dawley (not nephrectomised) and uninephrectomised rats receiving 3, 10, 30 or 100 ppm barium in distilled water or 0.9% saline for 16 weeks or in Dahl sodium sensitive rats receiving 1, 10, 100 or 1000 ppm barium in 0.9% saline. At the highest dose level (1000 ppm), there were ultrastructural changes in the glomeruli of the kidney, discernible by electron microscopy. No significant electrocardiographic changes were observed during L-norepinephrine challenge in Sprague-Dawley rats ingesting drinking water containing 250 ppm barium for 5 months. Histologic examination of 34 tissues showed no significant changes in male Sprague-Dawley rats receiving 1, 10, 100 or 250 ppm barium as barium chloride in drinking water (up to 150 mg/kg bw/day) for 36 or 68 weeks or female Sprague Dawley rats receiving 250 ppm barium chloride in drinking water for 46 weeks. No changes were noted in food consumption, body weight or incidence of tumours in the histology studies.

Dietz *et al.* (1992) completed a subchronic study of barium chloride dihydrate given for 92 days to B6C3F1 mice and Fischer 344/N rats in drinking water at concentrations of 0, 125, 500, 1000, 2000, and 4000 ppm. At 4000 ppm, mice were receiving 436 to 562 mg/kg bw/day, approximately 4 times the amount rats would receive based on their body weight. At 4000 ppm, mortality ranged from 60 to 70% in mice and from 10 to 30% in rats. Deaths in mice were associated with renal toxicity. Lesions were also present in kidneys from rats in the 4000 ppm group although they were less severe and were not present in all animals. Decreased body weight gain, increased serum phosphorus (rats only), lymphoid depletion and neurobehavioural changes were also seen in the groups receiving 4000 ppm barium chloride but were thought to be secondary to barium toxicity. The authors reported a no-observed-adverse-effect level (NOAEL) for this study of 2000 ppm barium chloride dihydrate in the drinking water (equivalent to 165 to 166 mg/kg bw/day in mice and 61 to 81 mg/kg bw/day in rats). Male and female reproductive and developmental endpoints are presented in section 4.7.1.

The National Toxicology Program (NTP) completed both subchronic and chronic studies on the effects of barium chloride in the drinking water of mice and rats. In the mouse study, male and female B6C3F1 mice (10 animals per dose group per sex) received barium chloride dihydrate in drinking water at concentrations of 0, 125, 500, 1000, 2000 and 4000 ppm for 13 weeks. The authors reported that these water concentrations corresponded to daily doses of 15, 55, 100, 205 and 450 mg/kg bw/day for the males and 15, 60, 110, 200 and 495 mg/kg bw/day for the females. Nephropathy and mortality were reported in male and female mice at 4000 ppm in drinking water. A drinking water concentration of 2000 mg/L (dose rates of 205 mg/kg bw/day in males and 200 mg/kg bw/day in females) was considered to represent the subchronic NOAEL (NTP 1994).

Groups of male and female F344/N rats (10 animals per dose group per sex) were exposed to barium chloride dihydrate in drinking water at concentrations of 0, 125, 500, 1000, 2000 and 4000 ppm for 13 weeks. The authors reported that these water concentrations corresponded to daily doses of 10, 30, 65, 110 and 200 mg/kg bw/day for the males and 10, 35, 65, 115 and 180 mg/kg bw/day for the females. Increased kidney weights were reported in female rats at water concentrations of 2000 ppm that corresponded to a dose rate of 115 mg/kg bw per day (i.e., the LOAEL) while the subchronic NOAEL was determined to be a drinking water concentration of 1000 mg/L (or a dose rate of 65 mg/kg bw per day for both sexes) (NTP 1994).

Male and female B6C3F1 mice (60 animals per dose group per sex) received barium chloride dihydrate in drinking water at concentrations of 0, 500, 1250 or 2500 ppm for 103 weeks (males) and 104 weeks (females). The authors reported that these concentrations corresponded to daily doses of 30, 75 and 160 mg/kg bw/day for males and 40, 90 and 200 mg/kg bw/day for females. Toxicologically significant effects (severe nephropathy and decreased survival) were reported in male and female mice at 2500 ppm in drinking water. A drinking water concentration of 1250 ppm (dose rates of 75 mg/kg bw/day in males and 90 mg/kg bw/day in females) represented the chronic NOAEL in mice (NTP 1994). No increases in malignant tumours or malignant tumor incidence were observed in any of the treated groups (up to 2500 ppm). The incidence of hepatocellular adenoma was significantly decreased in male mice receiving 2500 ppm barium chloride dihydrate.

Groups of male and female F344/N rats were exposed to barium chloride dihydrate in drinking water at concentrations of 0, 500, 1250, and 2500 ppm for 104 weeks (males) and 105 weeks (females). The authors concluded that these concentrations corresponded to daily doses of 15, 30 and 60 mg/kg bw/day for males and 15, 45 and 75 mg/kg bw/day for females. Similar to the subchronic study completed by the NTP, the most sensitive toxicological effect was increased kidney weights. Female rats were the most sensitive group with a reported LOAEL of 2500 ppm (or 75 mg/kg bw/day) and a NOAEL of 1250 ppm (or 45 mg/kg bw/day) (NTP 1994). No increases in malignant tumours or malignant tumor incidence were observed in any of the treated groups (up to 2500 ppm). Dose-related decreases were found in the incidence of adrenal medulla pheochromocytomas and mononuclear cell leukemia in male rats and mammary gland neoplasms in female rats.

4.5.2 Inhalation Exposure

Few animal studies have evaluated the toxicity of inhaled barium. Albino rats exposed to barium carbonate dust at an aerosol concentration of $33.4 \pm 3.6 \text{ mg/m}^3$ for one month demonstrated

changes to the red and white blood cells, inhibition of enzyme activity, altered metabolism, changes to vascular tone, altered liver function, bronchitis, thickening of the interalveolar septa and granular dystrophy in the heart, liver and kidneys (Tarasenko *et al.*, 1977).

Further study of the effects of barium carbonate dust was carried out in a chronic experiment on male albino rats to which the barium was administered by inhalation and intratracheally. Rats were exposed for 4 hours a day, 6 days a week for a period of 4 months to dust concentrations of $1.15 \pm 0.15 \text{ mg/m}^3$ or $5.20 \pm 0.25 \text{ mg/m}^3$. Animals exposed to 5 mg/m^3 of barium carbonate dust exhibited: reduced weight gain; higher arterial pressure; altered haematology parameters (reduced haemoglobin, leukocytosis and thrombopenia); altered serum chemistry parameters (decreased blood sugar and protein, increased phosphorus, decreased alkaline phosphatase and increased cholinesterase); increased calcium in the urine; impaired liver function and histological alterations in the heart, liver, kidneys and lung. Alterations in the lungs consisted of moderate perivascular and peribronchial sclerosis with focal thickening of the intraalveolar septa and collagenation. No changes were reported in rats exposed to 1 mg/m^3 barium carbonate dust (US EPA 1998; Tarasenko *et al.* 1977).

The Tarasenko *et al.* (1977) studies have been criticised for poor reporting of study design and results, lack of incidence data and lack of information on statistical analysis (ATSDR 2007; US EPA 1998).

No histological alterations were found in the lungs of Wistar rats exposed to 37.5 mg/m^3 of barium sulphate dust for 7 hours a day, 5 days a week for 203 days or 75 mg/m^3 of barium sulphate dust for 119 days (Cullen *et al.* 2000). No adverse effect level was identified in this study which examined only the respiratory tract.

4.6 Epidemiological Studies

4.6.1 Oral Exposure

Epidemiological studies of barium largely focus on the association between the barium content of drinking water and cardiovascular toxicity. Brenniman *et al.* (1979) examined cardiovascular mortality rates in Illinois communities with elevated barium concentrations in their drinking water (2–10 mg/L, approximately 0.04–0.2 mg barium/kg bw/day assuming water consumption of 1.5 L/day and body weight of 70.7 kg) and low barium concentrations in their drinking water (0.2 mg/L, approximately 0.004 mg barium/kg bw/day assuming water consumption of 1.5L/day and body weight of 70.7 kg). Communities exposed to elevated barium had significantly higher mortality rates for all cardiovascular diseases and for heart disease.

The lack of exposure data for individuals and the resulting inability to adjust rigorously for confounding factors and population mobility limit the usefulness of these studies in assessing cause-effect relationships. Moreover, the results of the cardiovascular mortality study conducted by Brenniman *et al.* (1979) were not confirmed in a cross-sectional study by Brenniman and Levy (1984). No significant differences were observed in the prevalence of hypertension, heart disease, stroke or kidney disease between residents of a community with a mean barium concentration in drinking water of 7.3 mg/L, (0.16 mg barium/kg bw/day) and residents of a community with a

mean barium concentration in drinking water of 0.1 mg/L, (0.0021 mg barium/kg bw/day) even when potential confounding factors were taken into account. Both studies lacked information on tap water consumption, barium intakes, and duration of exposure.

Wones *et al.* (1990) conducted a study examining the effects of barium chloride in drinking water on eleven male volunteers. Volunteers completed a 10-week dose-response protocol during which they were given of 1.5L of drinking water per day. The amount of barium chloride in the drinking water was gradually increased from 0 ppm (first 2 weeks), to 5 ppm (next 4 weeks), to 10 ppm (last 4 weeks). Diet and other aspects of the subjects' lifestyles known to affect cardiac risk factors were controlled during this period. Exposure to barium chloride in drinking water at concentrations of 5 and 10 ppm (equivalent to 0.11 and 0.21 mg/kg bw/day respectively, assuming a body weight of 70.7kg) did not result in any apparent changes to modifiable cardiovascular risk factors. Specifically, there was no increase in blood pressure, cholesterol, triglycerides, serum glucose or potassium levels. There was also no detectable effect of barium on catecholamine metabolism which could result in high blood pressure or serious arrhythmias. Furthermore, direct monitoring of heart rhythm showed no impact on several indices of cardiac irritability or arrhythmia potential.

4.6.2 Inhalation Exposure

Human data on the toxicity of inhaled barium compounds is limited. Most reports of barium toxicity involve occupational exposure to barium, barium sulphate, barite ore, or unspecified soluble barium compounds, and are limited by a lack of exposure information (ATSDR 2007; US EPA 1998). Baritosis, a benign pneumoconiosis, has been reported following inhalation of barium sulphate or barite ore (Seaton *et al.* 1986; Doig 1976). Due to the high radiopacity of barium, baritosis is visible on chest radiographs as discrete opacities. Following termination of exposure, these opacities have been shown to slowly disappear, suggesting a decrease in the amount of barium in the lung (US EPA 1998; Doig 1976). Baritosis is benign condition, and as such, is not known to result in toxicity.

Data from NIOSH (1982) suggest that barium inhalation may increase the incidence of hypertension, although, barium exposure levels were not actually measured in the group of workers with the increased incidence of hypertension. Workers were also exposed to other metals, including lead, which is known to be hypertensive (US EPA 1998).

4.7 Reproductive and Developmental Effects

4.7.1 Oral Exposure

Dietz *et al.* 1992 evaluated reproductive and developmental endpoints in male and female Fischer 344/N rats and B6C3F1 mice exposed to barium chloride dihydrate in drinking water. Rats were exposed to 1000, 2000, or 4000 ppm barium chloride dihydrate in drinking water and mice were exposed to 500, 1000, or 2000 ppm barium chloride in drinking water. While estimated barium doses were not provided, this study was a preliminary report conducted by the same authors as the NTP 1994 studies. If approximate doses are taken from NTP 1994 the estimated barium doses for rats were 0, 65, 110, and 200 mg/kg-day for males and 0, 65, 115, and 180 mg/kg-day for females. Estimated barium doses for mice were 0, 55, 100, and 205 mg/kg-day for males and 0,

60, 110, and 200 mg/kg-day for females (US EPA 1998). Following exposure (60 days for males, 30 days for females), males and females from the same exposure groups were housed together until evidence of mating was found (up to 8 days cohabitation).

Pregnancy rates in the rat study were below normal in all groups (40% of expected rate in controls, 65% of expected rate in the 4000 ppm group). This problem was not corrected by remating due to restrictions in the study design and dosing schedule. No significant alterations were seen in gestation length, pup survival or occurrence of external abnormalities. Number of implants per pregnant dam and litter size at birth and postpartum day 5 were marginally reduced in pups from the high dose group (4000 ppm) compared to controls but these results were not statistically significant. A significant, although marginal, reduction in pup weights was seen in rats receiving 4000 ppm barium chloride, however, this reduction was not observed at 5 days of age.

Pregnancy rates in mice were 55% in the controls and ranged from 55-70% in the barium treated groups. No significant alterations were seen in gestation length, maternal weight gain, pup survival, pup weights or occurrence of external abnormalities. A significant decrease was seen in litter size on days 0 and 5 for mice in the 1000 ppm group compared to controls but was not observed in the high dose group (2000 ppm). No effects were seen on sperm parameters, or vaginal cytology in either species at any dose (up to 2000 ppm in mice and 4000 ppm in rats),

No histological alterations were observed in the reproductive tissues of male and female rats and mice exposed to barium chloride in drinking water in the subchronic and chronic NTP studies (NTP 1994) or in male or female rats exposed to barium chloride in drinking water in the histology study by McCauley *et al.* (1985). Details of both studies are described in section 4.6.1

Tarasenko *et al.* (1977) performed a number of experiments to examine the effects of inhaled or orally administered barium carbonate dust on reproductive function and offspring of male and female rats. Oral administration of 1/16 of the LD₅₀ (26.125 mg/kg of barium carbonate to female rats for 24 days before conception and throughout pregnancy caused an increase in mortality of the offspring for two months after birth. Examination of the offspring revealed increased leukocyte counts in the blood, disturbances in liver function, and increased urinary excretion of hippuric acid (Tarasenko *et al.* 1977). It should be noted that the data presented in this publication were insufficient to permit proper evaluation of the methods or results of these studies. These studies lacked information on experimental methods, including whether controls were used and the number of animals used, exposure conditions, statistical methods and test results (ATSDR 2007; US EPA 1998).

4.7.2 Inhalation Exposure

An inhalation study in female rats exposed to 3.1 ± 0.16 or 13.4 ± 0.7 mg/m³ barium carbonate dust for four months reported shortening of the duration of the oestrous cycle and disturbances in the morphological structure of the ovaries in animals from the high dose group (13 mg/m³ barium carbonate dust). Offspring of dams in the high dose group exhibited increased mortality and reduced body weight gain compared to offspring of control dams. At 2 months of age, the offspring exhibited decreased lability of the peripheral nervous system, and blood disorders (erythropenia,

leukocytosis, eosinophilia, neutrophilia) which the authors attributed to an irritant effect of barium on the bone marrow.

A similar inhalation study in male rats exposed to 22.6 ± 0.6 mg/m³ barium carbonate dust for one cycle of spermatogenesis, resulted in deleterious effects on spermatogenesis including decreased number of spermatozooids, decreased percentage of motile forms and time of motility, decreases in osmotic resistance of spermatozooids, increases in the number of ducts with desquamated epithelium and a reduced number of ducts with 12th stage meiosis (Tarasenko *et al.* 1977). These studies suffer from the same data insufficiencies as presented above (section 4.7.1). Duration of daily exposure or frequency of exposure were not reported and it is not clear if exposed females were mated to exposed or un-exposed males (US EPA 1998).

4.8 Carcinogenicity and Genotoxicity

At the current time no major health agency considers barium to be carcinogenic following oral exposure. The lack of data available regarding the carcinogenicity of barium has resulted in it being classified in group VA (inadequate data for classification) by Health Canada (HWC 1990). A similar classification (Class D) was adopted for barium by US EPA (1998) under EPA's *Guidelines for Carcinogen Risk Assessment* (US EPA 1986). Under the *Proposed Guidelines for Carcinogen Risk Assessment* (US EPA 1996), barium is considered not likely to be carcinogenic to humans following oral exposure. The carcinogenicity of inhaled barium cannot currently be assessed due to the lack of inhalation exposure data (ATSDR 2007; US EPA 1998). The IARC has not classified barium with regards to carcinogenicity. Barium is therefore treated as a threshold toxicant for the development of human health soil quality guidelines.

No data are available regarding the carcinogenic potential of barium following oral or inhalation exposure in humans. Chronic oral exposure studies in rodents have not demonstrated carcinogenicity (NTP 1994; McCauley *et al.* 1985; Schroeder and Mitchener 1975a,b).

There was no evidence of tumours upon gross examination at autopsy in the lifetime bioassays of rats and mice exposed to 5 ppm barium acetate in drinking water completed by Schroeder and Mitchener (1975 a,b), as discussed in section 4.5.1. In addition, there was no evidence of increased tumour incidence in male Sprague-Dawley rats receiving 1, 10, 100 or 250 ppm barium as barium chloride in drinking water (up to 150 mg/kg bw/day) for 36 or 68 weeks or female Sprague Dawley rats receiving 250 ppm barium chloride in drinking water for 46 weeks (McCauley *et al.* 1985). These studies are considered inadequate for evaluating the carcinogenic potential of barium. Both studies used only one exposure dose and it is not clear whether a maximum tolerated dose was achieved. The McCauley *et al.* (1985) used a small number of animals and was not of a sufficient duration for a carcinogenicity study. In the Schroeder and Mitchener studies (1975a,b) complete histological examinations were not performed.

No evidence of carcinogenicity was found in chronic oral exposure studies in rats and mice conducted by NTP (1994) as discussed in section 4.5.1. These studies are considered adequate for evaluating carcinogenicity (ATSDR 2007; US EPA 1998).

No data are available regarding cancer in humans or animals after inhalation or dermal exposure to barium. Dysplasia of the cervical epithelium was reported following a single topical application of 1.25mM barium chloride to the cervix (Ayre 1966 as cited in US EPA 1998). These alterations were no longer present observed 3 weeks after the application.

The available weight of evidence suggests that barium does not induce genetic mutations in bacterial assays, with or without activation (US EPA 1998). Negative results were obtained with barium chloride in the Ames assay (*Salmonella typhimurium*), with and without metabolic activation (NTP 1994; Monaco *et al.* 1990). Barium chloride did not increase the frequency of mutation in repair-deficient strains of *Bacillus subtilis* (Nishioka 1984). Barium chloride induced gene mutations in L5178Y mouse lymphoma cells with metabolic activation, but not without metabolic activation (NTP 1994). Barium chloride did not induce sister chromatid exchanges or chromosomal aberrations in cultured Chinese hamster ovary cells, with or without activation (NTP 1994).

Barium nitrate was non-mutagenic using the Ames assay (*Salmonella typhimurium*) with and without metabolic activation and the mitotic crossing over test, the mitotic gene conversion test, and the retromutation test in *Saccharomyces cerevisiae*, D7 strain with and without metabolic activation (Monaco *et al.* 1991).

Wise *et al.* (2003) investigated the cytotoxicity and clastogenicity of barium chromate on WTHBF-6 human lung cells. Barium chromate induced concentration-dependent cytotoxicity with relative survival of 88%, 74%, 67%, 12%, 3% and 0.1% after exposure to 0.01, 0.05, 0.1 0.5, 1 and 5 $\mu\text{g}/\text{cm}^2$ barium chromate. A 24 hour exposure period also induced concentration-dependent increases chromosomal damage. 0.01, 0.05, 0.1, and 0.5 $\mu\text{g}/\text{cm}^2$ barium chromate damaged 5%, 9%, 22% and 49% of metaphase cells with total damage reaching 5, 10, 28, and 65 aberrations per 100 metaphases, respectively. Further research is needed to determine if barium or chromium ions play a role in the carcinogenicity of barium chromate.

Results of *in vivo* genotoxicity tests are limited to a single study in *Drosophila melanogaster* (Yesilada 2001). Although a high concentration (10mM) of barium nitrate gave positive results for small single spots, results from low concentrations (1mM) were inconclusive. Small single spots in the SMART test are assumed to be indicative of gene mutations, chromosomal deletion, non-disjunction or mitotic recombination. Barium nitrate was not indicative of genotoxic activity.

4.9 Toxicological Limits

For the purpose of calculating a soil quality guideline, the reference dose (RfD) of 0.2 mg/kg bw/day recommended by US EPA was adopted. The US EPA (2005) RfD of 0.2 mg/kg bw/day is based on nephropathy observed in mice in the 1994 NTP study. Using benchmark dose modelling, a BMDL₀₅ of 63 mg/kg bw/day was selected as a point of departure for the RfD. Ten-fold uncertainty factors were applied for both interspecies and intraspecies variability as well as a three-fold uncertainty factor to account for deficiencies in the database. Similarly, the Agency for Toxic Substances Disease Registry (ATSDR 2007) also developed a Minimal Risk Level (MRL) of 0.2 mg/kg bw/day for chronic exposures (>365 days) based on the NTP (1994) study. The MRL is based on a BMDL₀₅ of 61 mg barium/kg/day for nephropathy in mice. Ten-fold uncertainty

factors were applied for interspecies and intraspecies variability and a modifying factor of three was used to account for the lack of an adequate developmental toxicity study (ATSDR 2007).

The CICAD (2001) provides a tolerable daily intake of 0.02 mg/kg bw/day based on a NOAEL of 0.2 mg/kg bw/day from the controlled human exposure study by Wones *et al.*, (1990) and the epidemiological study by Brenniman and Levy (1984). The CICAD applied a 10-fold uncertainty factor to the NOAEL from both studies to account for database deficiencies and potential differences between adults and children.

The California EPA (Cal OEHHA 2003) derived a Public Health Goal (PHG) of 2mg/L based on a NOAEL of 0.2 mg/kg bw/day from the the epidemiological study by Brenniman and Levy (1984) study and supported by the human exposure study by Wones *et al.* (1990). A three-fold uncertainty factor was applied for intraspecies variability.

For the current assessment, the US EPA (2005) RfD of 0.2 mg/kg bw/day RfD was adopted as the tolerable daily intake (TDI) for estimating human health soil quality guidelines for barium. As stated by the US EPA, hypertensive effects have been seen following barium exposure but results are often conflicting. The studies by Wones *et al.* (1990) and Brenniman and Levy (1984) did not provide sufficient data to support the hypothesis that chronic barium exposure causes hypertension. The TDI should not be based on these studies due to the absence of sufficient dose-response data. Nephropathy observed in the 1994 NTP study considered to be the most sensitive endpoint for barium toxicity, with a dose-response relationship.

At the present time there is insufficient evidence to support a relative oral bioavailability for barium in soil of less than 100% for the purposes of guideline development.

Inhalation and dermal studies in humans and animals are not adequate to derive TDIs for barium at the present time.

5. DERIVATION OF HUMAN HEALTH SOIL QUALITY GUIDELINES

The *Protocol for the Derivation of Environmental and Human Health Soil Quality Guidelines* (CCME 2006) can be used to establish guidelines for agricultural, residential/parkland, commercial and industrial land uses. This guidance document was used to calculate the soil quality guidelines for barium presented in this document.

5.1 Protocol

As indicated in the previous section, an oral tolerable daily intake (TDI) of 0.2 mg/kg bw/day (200 µg/kg bw/day) was adopted for barium based on US EPA (2005) RfD. The oral TDI was applied to the dermal and inhalation exposure, as no toxicity reference values were identified for these routes of exposure. Barium is considered to be non-carcinogenic.

For substances, such as barium, for which the critical effect is believed to have a threshold (e.g., below a certain point of exposure no adverse effects are anticipated), two key factors are considered for setting soil quality guidelines. First, it is recognised that, exclusive of hazardous

waste sites or any other point source of pollution, everyone is exposed to a "background" level of substances that cannot be avoided. For barium, this background exposure is primarily from food for Canadians. In setting soil quality guidelines for barium, the background estimated daily intake (EDI) was subtracted from the Tolerable Daily Intake (TDI) before the soil quality guidelines were calculated.

Secondly, a multimedia approach to guidelines development has evolved whereby guidelines for one medium are established recognising that guidelines for other media may also be required. Guidelines must be established in a manner such that total simultaneous exposure at the guideline levels for all media will not result in exposure which exceeds the TDI. Therefore, in order to set soil quality guidelines for threshold substances, some portion of the residual tolerable daily intake (TDI minus EDI) must be attributed to each medium. A simple, arbitrary and practical solution was applied to this problem. With five primary media to which people are exposed (air, water, soil, food and consumer products), 20% of the residual tolerable daily intake for threshold (non-carcinogenic) substances is apportioned to each of these media (as per CCME 2006).

In order to calculate a quantitative soil quality guideline, it is necessary to define one or more scenarios by which exposure will occur. As 80% of Canadians live in cities (Statistics Canada 2006), an urban exposure scenario is the most common.

5.2 Estimated Daily Intake

Estimated daily intakes (EDIs) for the Canadian population have been calculated on the basis of the environmental concentration of barium in uncontaminated environmental media (see section 2.5). In general, the EDI is an estimate of the typical total concurrent background exposure from all known or suspected sources via a multimedia exposure assessment for the average Canadian. It does not include exposures that may occur from a contaminated site, or activities that may result in increased exposure of substances that are not considered background exposure. The EDI calculation is illustrated in the equation (CCME 2006).

$$EDI = \sum_{i=1}^n ED_i$$

The EDIs are expressed in units of $\mu\text{g}/\text{kg bw}/\text{day}$ and they are intended to represent the average exposure that the Canadian population may receive from barium. The general population was subdivided into five age classes: infants (birth to 6 months), toddlers (7 months to 4 years), school age children (5 to 11 years), teenagers (12 to 19 years) and adults (20 years and older). The following media were considered in calculating the EDI: ambient air, indoor air, indoor dust, soil, drinking water, food and breast milk. Consumer products were not included in the EDI estimation because there is limited data in this area. The equation below illustrates the media and pathway-specific EDI calculation (CCME 2006).

$$ED_i = \frac{C \times CR \times BF \times EF}{BW}$$

where,

ED_i = exposure dose from pathway i (mg/kg-day)

C = contaminant concentration in medium (e.g., mg/L)

CR = media specific contact rate (e.g., L/day)

BF = bioavailability factor (unitless)

EF = exposure factor which is the product of the exposure frequency (events/year) and exposure duration (years/lifetime) and is unitless

BW = body weight (kg)

Concentrations of barium in environmental media were obtained from governmental databases, scientific literature and grey literature as outlined in section 2.5 and presented in Appendix 3.

Receptor characteristics and intake rates for each age class were treated as probability distribution functions (PDFs) as described in Health Canada 2011. PDFs were assumed to be lognormal except for human breast milk intake and time spent outdoors. A triangular distribution was used for human breast milk intake because of limited availability of data.

PDFs were generated for concentrations in environmental media, receptor characteristics and intake rates. These were used to generate EDI distributions by age group for each media and a combined total EDI from all media and exposure routes. Receptor characteristics and intake rate distributions are presented in Appendices 4 and 5. Appendix 6 summarises the daily intake estimates for barium via all media for five age groups of the Canadian general population.

The total barium EDIs for adults, teenagers, children and toddlers are 7.5, 9.5, 17, and 24 µg/kg bw/day (median values). Depending on whether infants are exclusively formula fed, exclusively breast fed or fed a mixture of breastmilk, infant formula and table food, the EDI for infants can be 1.3 µg/kg bw/day (exclusively breastfed) or 22 µg/kg bw/day (non-breastfed). For the purpose of soil quality guidelines derivation, the EDI for toddlers and adults were used.

Certain Canadian subpopulations may be exposed to higher levels of barium. Naturally occurring high levels of barium in drinking water have been found in various locations in Canada. Consumption of such waters would be the most likely route for higher Canadian exposure to barium. Consumption of food grown on soils containing high levels of barium could also possibly increase barium exposure above the levels calculated in the present exposure analysis. In addition, people living near industrial areas associated with barium emissions could be exposed to higher concentrations of barium via inhalation of ambient air. Due to insufficient data, it is not possible, at this time, to perform an exposure assessment for those groups. However, the current analysis does suggest that, next to the consumption of food, the direct contact pathways for soil (incidental ingestion, inhalation and dermal contact) are small contributors to total barium exposure.

5.3 Exposure Limits for Human Receptors

As stated in section 4, the US EPA (2005) RfD of 0.2 mg/kg bw/day (200 µg/kg bw/day) reference dose was considered to be appropriate as the tolerable daily intake for calculating soil quality guidelines for barium. Insufficient data were available for derivation of an exposure limit for inhalation or dermal exposure, thus the oral TDI was used to estimate toxicity from inhalation and dermal routes of exposure.

5.4 Relative Absorption Factors

Relative absorption factors may be applied when the critical toxicological study has used a different medium than that under investigation, in order to account for the difference in absorption of the substance via different exposure routes or in different media.

The TDI used for this SQG was based on a drinking water study where barium chloride was administered to mice. The oral bioavailability of barium in soil may vary significantly depending on factors such as soil conditions, the form of barium present in the soil and gastrointestinal conditions; however, insufficient information is available to determine the bioavailability of barium in soils. Therefore, a relative absorption factor of 100% was selected for exposure via ingestion. Similarly, no data were available for bioavailability via inhalation, and a factor of 100% was selected.

OMOE (2008) as referenced in Health Canada's draft PQRA Part II 2010, recommends a dermal relative absorption factor of 0.1 as a generic default assumption for metals in general which is not specific for barium (Health Canada 2010b). Quantitative data are insufficient to estimate the dermal absorption factor for barium; therefore, the OMOE selected the default RAF of 0.1 using an order-of-magnitude approach (default absolute dermal absorption of 1% is approximately an order of magnitude lower than the estimated absolute oral absorption). The absolute dermal absorption value was estimated using a comparison approach of data-derived estimates recommended by international organisations (i.e. US EPA and CalEPA) for various inorganics (OMOE 2011).

For the purposes of this assessment, a relative absorption factor of 0.1 (10%) was used for dermal exposure.

5.5 Ingestion, Inhalation and Dermal Pathways

5.5.1 Agricultural and Residential/Parkland Land Uses

Agricultural lands are characterised by the presence of a farm with a family, including children, where residents consume the produce, meat, and milk produced on-site, and groundwater may be used as potable water (50% of produce may be consumed from the agricultural site as well as 50% of meat and 100% of milk). In a residential/parkland setting, the receptors may have access to a backyard, and it is assumed that up to 10% of produce is grown on-site. In both cases, the most sensitive receptor is the toddler, as this age category has the largest exposure to body weight ratio.

Using the above assumptions, a soil quality guideline for direct exposure to soils that applies to agricultural and residential/parkland land uses can be determined using the equation below from CCME (2007) protocol:

$$SQG_{DH} = \frac{(TDI - EDI) \times SF \times BW}{[(AF_G \times SIR) + (AF_S \times SR) + (AF_L \times IR_S) \times ET_2] \times ET_1} + BSC$$

where,

- SQG_{DH} = direct human health-based soil quality guideline (mg/kg)
TDI = tolerable daily intake by oral route of exposure = 0.2 mg/kg bw/day (US EPA 2005);
EDI = estimated daily intake = 0.024 mg/kg bw/day for toddler (Appendix 6);
SF = soil allocation factor (20% by default) = 0.2 (CCME 2006);
BW = body weight for a toddler (16.5 kg) (CCME 2006);
 AF_G = relative absorption factor for barium across the gut (100%) = 1.0 (CCME 2006);
SIR = soil ingestion rate for a toddler (8×10^{-5} kg/d) (CCME 2006);
 AF_S = relative absorption factor for barium across the skin (10%) = 0.1 (section 5.4);
SR = soil dermal contact rate for toddler = 6.9×10^{-5} kg/d [hands surface area of 0.043 m^2 x soil adherence factor of $0.001 \text{ kg/m}^2/\text{d}$ + arms/legs surface area of 0.258 m^2 x soil adherence factor of $0.0001 \text{ kg/m}^2/\text{d}$ (all parameters from CCME 2006)];
 AF_L = relative absorption factor for barium across the lungs (100%) = 1.0 (CCME 2006);
 IR_s = soil inhalation rate for toddler = 6.3×10^{-9} kg/d [i.e., inhalation rate for toddler = $8.31 \text{ m}^3/\text{d}$ x suspended soil dust concentration of $7.6 \times 10^{-10} \text{ kg/m}^3$ (Health Canada 2010a)];
 ET_1 = exposure term 1 (unitless) days per week/7 x weeks per year/52 at the site = 1.0 [i.e., 7 days per week, 52 weeks per year assumed at the site (CCME 2006)];
 ET_2 = exposure term 2 (unitless) – hours per day/24 at the site = 1.0 [i.e., 24 hours per day assumed at the site (CCME 2006)];
BSC = background soil concentration = 140 mg/kg (Appendix 3);

therefore,

SQG_{DH} = **6800 mg/kg** barium in soil at agricultural and residential/parkland sites.

5.5.2 Commercial Land Use

Commercial sites include such places as shopping malls and places of business. Access to the site is not restricted, and since some commercial properties may include daycare facilities, the critical receptor is the toddler. Commercial sites do not include any areas where manufacturing takes place, nor areas where individuals may reside.

Since access to commercial sites is not assumed to be 24-hours, exposure assumptions are appropriately less than for residential land use. Discretion should be used in employing the commercial land use classification – in scenarios where unrestricted 24-hour access by children or toddlers, or residential occupancy by any individual is possible, the residential/parkland classification may be more appropriate.

The toddler is assumed to be the most sensitive receptor at commercial sites. The commercial land use calculation is exactly the same as the Agricultural and Residential/Parkland calculations, the only differences being:

- exposure term 1 (ET_1) is 0.66 (based on 5 d/wk and 48 wk/y) due to the reduced amount of time the receptor spends on a commercial site.

- exposure term 2 (ET₂) is 0.42 (based on 10 h/d) due to the reduced amount of time the receptor spends on a commercial site.

The direct human health-based soil quality guideline (SQG_{DH}) for barium on commercial lands was calculated to be **10 000 mg/kg**.

5.5.3 Industrial Land Use

Industrial lands typically have limited or restricted access to the public so that adult, occupational exposure will predominate. The most common exposure scenario is expected to be unintentional soil ingestion by an adult. The potential for off-site migration of substances (i.e. via soils and dust) may need to be evaluated for industrial land use scenarios. Exposure for an adult at an industrial site is assumed to be 10 h/d, 5 d/wk and 48 wk/y. An example of industrial land use is a manufacturing plant.

Using the above assumptions, a soil quality guideline that applies to industrial land use is:

$$SQG_{DH} = \frac{(TDI - EDI) \times SF \times BW}{[(AF_G \times SIR) + (AF_S \times SR) + (AF_L \times IR_S) \times ET_2] \times ET_1} + BSC$$

where,

SQG_{DH} = human health-based soil quality guideline (mg/kg)

TDI = tolerable daily intake by oral route only = 0.2 mg/kg bw/day (US EPA 2005);

EDI = estimated daily intake for an adult = 0.0074 mg/kg bw/day (Appendix 6);

SF = soil allocation factor (20% by default) = 0.2 (CCME 2006);

BW = body weight for an adult = 70.7 kg (CCME 2006);

AF_G = relative absorption factor for barium across the gut (100%) = 1.0 (CCME 2006);

SIR = soil ingestion rate for an adult = 2 × 10⁻⁵ kg/d (CCME 2006);

AF_S = relative absorption factor for barium across the skin (10%) = 0.1 (section 5.4);

SR = soil dermal contact rate for an adult = 1.14 × 10⁻⁴ kg/d [hands surface area of 0.089 m² x soil adherence factor of 0.001 kg/m²/d + arms surface area of 0.25 m² x soil adherence factor of 0.0001 kg/m²/d (all parameters from CCME 2006)];

AF_L = relative absorption factor for barium across the lungs (100%) = 1.0 (CCME 2006);

IR_S = soil inhalation rate for an adult = 1.3 × 10⁻⁸ kg/d [i.e., inhalation rate for an adult = 16.57 m³/d x suspended soil dust concentration of 7.6 × 10⁻¹⁰ kg/m³ (Health Canada 2010a)]

ET₁ = exposure term 1 = 0.66 [5 days per week/7 × 48 weeks per year/52 at the site (CCME 2006)]

ET₂ = exposure term 2 = [0.42 – 10 hours per day/24 at the site (CCME 2006)]

BSC = background soil concentration = 140 mg/kg (Appendix 3)

therefore,

SQG_{DH} = **130 000 mg/kg** barium in soil for industrial sites.

5.6 Protection of Groundwater Used as a Source of Raw Water for Drinking

No guideline for protection of groundwater used as a source of raw water as drinking water was calculated for barium (as total) due to constraints on the mathematical model when applied to inorganic compounds (CCME 2006).

5.7 Guideline for Consumption of Produce, Meat and Milk

The check mechanism for consumption of produce, meat and milk was not calculated for barium because it is not a substance that is expected to biomagnify as discussed in Section 3.6. It is recognised that CCME SQG protocol (2006) assumes the consumption of product, meat and milk for agricultural land use and the consumption of produce for residential land use. The SQG_{HH} for barium was only calculated for direct contact (ingestion, inhalation and dermal contact) with soil. Concerns regarding barium exposure through the consumption of produce, meat and milk should be addressed on a site-specific basis.

5.8 Guideline for Off-site Migration for Commercial and Industrial Land Uses

In the calculation of Soil Quality Guidelines for Commercial and Industrial sites, only exposure scenarios for on-site exposure are considered. Transfers of contaminated soil, from one property to another are possible by environmental fate and transport mechanisms such as wind and water erosion (CCME 2006).

The Universal Soil Loss Equation and the Wind Erosion Equation are used to estimate the transfer of soil from one property to another. The following equation allows us to calculate the concentration in eroded soil from the site that will raise the substance concentration in the receiving soil to equal the agricultural guideline within a specific time frame. This concentration is referred to as the human health soil quality guideline for off-site migration (SQG_{OM-HH}). If the guidelines for commercial or industrial sites are found to be above SQG_{OM-HH} , then the adjacent property could potentially become contaminated from off-site deposition (CCME 2006). The following equation has been derived to allow the calculation of SQG_{OM-HH} .

$$SQG_{OM-HH} = 14.3 \times SQG_A - 13.3 \times BSC$$

where,

SQG_{OM-HH} = human health soil quality guideline for off-site migration (i.e., the concentration of substance in eroded soil (mg/kg))

SQG_A = soil quality guideline for agricultural land uses (6800 mg/kg)

BSC = background concentration of barium in soil (140 mg/kg)

The SQG_{OM-HH} for commercial and for industrial land uses was calculated to be 96 000 mg/kg), which is more than the SQG_{HH} for commercial (10 000 mg/kg) but less than the industrial (130 000 mg/kg) land uses. Therefore, the commercial SQG_{HH} does not need to be modified to protect against off-site migration; however, the industrial SQG_{HH} does need to be modified to protect against off-site migration.

5.9 Final Human Health Soil Quality Guidelines

Based on CCME (2007) protocol, three types of exposure pathways are evaluated: required pathways, applicable pathways and check mechanisms. The SQGs for each of the pathways calculated are listed in Table 4 (next section).

Human health soil quality guidelines were calculated for screening barium in soils, based on ingestion, inhalation and dermal contact with soil. The proposed human health soil quality guidelines for direct exposure to soil via ingestion, inhalation and dermal contact for agricultural and residential/parkland land uses is 6800 mg/kg soil, 10 000 mg/kg soil for commercial land use and the and 130 000 mg/kg soil for industrial land uses.

While the SQG_{HH} provided above are considered to be protective at most sites not all exposure pathways have been evaluated such as barium levels in garden produce, meat, milk consumption or barium leaching from soils to groundwater or surface water used for drinking water. A site specific risk assessment and sampling of additional media may be warranted at sites where these media may be impacted by elevated levels of barium in soil.

With the above in mind, the SQG_{HH} are considered to be protective of human health at most sites. These SQG_{HH} are not applicable to barite contaminated sites and should not be used at sites where barite is naturally occurring or is a known contaminant of concern (i.e. documented use of barite). These sites should be addressed on a site specific basis.

6. RECOMMENDED CANADIAN SOIL QUALITY GUIDELINES

According to the formal protocol (CCME 2006), 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 CCME as the Canadian Soil Quality Guideline. The environmental soil quality guidelines for barium are not currently being updated; therefore, final Soil Quality Guidelines for the protection of environmental and human health cannot be developed at this point in time. The recommended Canadian Soil Quality Guidelines for the protection human health are presented below in Table 4.

Table 4. Soil quality guidelines and check values for barium (mg·kg⁻¹).

Guideline	Land use			
	Agricultural	Residential/ parkland	Commercial	Industrial
	750 ^a	500 ^a	2000 ^a	2000 ^a
Human health guidelines/check values				
SQG _{HH}	6800 ^b	6800 ^b	10 000 ^b	96 000 ^b
Direct contact guideline	6800 ^c	6800 ^c	10 000 ^c	130 000 ^c
Inhalation of indoor air check	NC ^d	NC ^d	NC ^d	NC ^d
Off-site migration check	—	—	96 000	96 000
Groundwater check (drinking water)	NC ^e	NC ^e	NC ^e	NC ^e
Produce, meat, and milk check	NC ^f	NC ^f	—	—
Environmental health guidelines/check values				
SQG _E	NC ^g	NC ^g	NC ^g	NC ^g
Soil contact guideline	NC	NC	NC	NC
Soil and food ingestion guideline	NC	—	—	—
Nutrient and energy cycling check	NC	NC	NC	NC
Off-site migration check	—	—	NC	NC
Groundwater check (aquatic life)	NC ^e	NC ^e	NC ^e	NC ^e
1999 Barium Soil Quality Guideline (CCME 1999)	750	500	2000	2000
Interim soil quality criterion (CCME 1991)	750	500	2000	2000

Notes: NC = not calculated; ND = not determined; SQG_E = soil quality guideline for environmental health; SQG_{HH} = soil quality guideline for human health. The dash indicates a guideline/check value that is not part of the exposure scenario for this land use and therefore is not calculated.

^aData are sufficient and adequate to calculate only a SQG_{HH}. It is greater than the corresponding interim soil quality criteria (CCME 1991). Therefore the interim soil quality criterion (and 1999 soil quality guideline) is retained as the soil quality guideline for this land use.

^bThe SQG_{HH} is the lowest of the human health guidelines and check values.

^cThe direct human health-based soil quality guideline is based on direct exposure to soil ingestion, dermal contact, and particulate inhalation.

^dThe inhalation of indoor air check applies to volatile organic compounds and is not calculated for metal contaminants.

^eApplies to organic compounds and is not calculated for metal substances. Concerns about metal substances should be addressed on a site specific basis.

^fThis check is intended to protect against chemicals that may biomagnify in human food. Barium is not expected to exhibit this behaviour, therefore this pathway was not evaluated.

^gData are insufficient/inadequate to calculate an SQG_E, or provisional SQG_E for this land use. The environmental soil quality guidelines for barium were not updated in 2012. For more information on the environmental soil quality guidelines for barium and its effects on ecological receptors, consult EC (1999).

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Appendix 1. Summary tables of barium concentration in environmental media

Ambient/Outdoor Air

Location	Year	Concentration ng/m ³	Range ng/m ³	Comments	Reference
Canada British Columbia, Ontario, Quebec, New Brunswick	2003-2009	1.9 (mean)	0 - 30	NAPS data, PM _{2.5} fraction analysed by ICP-MS following acid digestion.	Environment Canada 2011.
	2002	14	1.2 – 115.1	Coarse particulate matter (PM ₁₀) for NAPS stations across Canada. Elemental concentrations were obtained using nondestructive x-ray fluorescence techniques	Burnett <i>et al.</i> 2000; Environment Canada 2003; Peris 2004 <i>pers com.</i>
Canada (excluding Yukon, PEI and Newfoundland)	2001	-	2.1 – 23.2		
	2000	-	2.0 – 9.9		
Canada Montreal, Ottawa, Toronto, Windsor, Winnipeg, Calgary, Edmonton and Vancouver	1984-1994	5.4 (mean) 13.3 (95 th percentile)	-	Only 27% of 4255 samples collected were above the analytical detection limit (average detection limit = 7.4 ng/m ³ over the sampling period).	Burnett <i>et al.</i> 2000.
Canada 19 sites across the country within 12 major cities, one rural area and one industrial area	1992	75 (maximum)	-	80% of samples were below the detection limit of 11.9 ng/m ³ .	CCME 1999.
Newfoundland Corner Brook	-	10 (mean) 111 (maximum)	-	78% of samples were below the detection limit of 9 ng/m ³ . The 40 samples collected were analysed by XRF.	Jeans 1991 <i>pers com.</i>
Quebec Municipality of Shawinigan	2000 1999	17 (95 th percentile) 20 (95 th percentile)	-	Concentrations were below the analytical detection limit of 20 ng/m ³ for 75% of samples in 1999 and 42% in 2000.	Bisson 2004 <i>pers com.</i>
Ontario London	2010	17.9 (mean, heavy traffic site) 3.9 (mean, urban background sites)	-	Barium was found to comprise 1.1% of brake wear particles (PM ₁₀) from traffic fleet as a whole which enables its use as a quantitative tracer of brake wear emissions at traffic influences sites.	Gietl <i>et al.</i> 2010.
Ontario Durham and York Regions	2009	4.9 (annual baseline concentration; max, UCLM or MDL)	-	Sampling completed in vicinity of development for Municipal Energy from Waste Facility in Municipality of Clarington, ON	Jacques Whitford Ltd. 2009.
Ontario Burnt Island, Egbert and Point Petre	1995-1998	-	1.38 – 1.6	Barium was detected in the majority (92%) of the 324 samples collected. The analytical detection limits reported for barium during this time period were varied, ranging from 0.08 to 0.53 ng/m ³	Dryhout-Clark 2004 <i>pers com.</i>
Alberta Edmonton	1994-2000	PM _{2.5} 2.7 (1994) – 1.1 (2000) PM ₁₀ 8.3 (1994) – 3.4 (2000)	-		Myrick 2004 <i>pers com.</i>
		PM _{2.5} 3.5 (1994) – 2.1 (1999)	-		
Calgary	1994-1999	PM ₁₀ 18.1 (1994) – 7.8 (1999) (mean concentrations)	-		

Location	Year	Concentration ₃	Range ng/m ³	Comments	Reference
British Columbia Burnaby Lake	2001	240 (mean)	5.2 - 1100	Sampled from a highly urbanised and industrial area, n=16. Analysed by ICP-AES. Limit of detection 2.5 ng/m ³ (All samples greater than the detection limit).	Brewer and Belzer 2001.
Canadian Arctic Alert, NU	1980-81 1991-82	(mean concentrations) 0.5 0.37			
Igloodik, NU	1980-81 1991-82	0.16 0.21	NA	Analysed by ICP. Detection limit range was 0.04 to 0.07 ng/m ³	Barrie and Hoff 1985.
Mould Bay, NWT	1980-81 1991-82	0.42 0.47			

Indoor Air

Location	Year	Concentration ng/m ³	Range ng/m ³	Comments	Reference
Alberta High Level	1998	9 (mean; PM ₁₀) 502 (mean; PM _{2.5})	-	-	Alberta Health 1998.
United States Baltimore, MD	2003	0.33 (median)	-	PM _{2.5} sampled and analysed by ICP-MS following partial digestion.	Graney <i>et al.</i> 2004.
United States Various urban and suburban locations	1958	-	<5-1500	-	Tabor and Warren 1958.

Indoor Dust

Location	Year	Concentration mg/kg	Range mg/kg	Comments	Reference
Ontario Ottawa	2001	492 (mean)	190 – 1480	House dust samples were analysed by ICP-MS with a Ba detection limit of 1 mg/kg.	Rasmussen <i>et al.</i> 2001.
United States Arizona	1995-1997	228.7 (mean)	73.54 - 889.2	n=117, SD=136.17	US EPA 2009.

Soil

Location	Year	Soil type	Sample Depth	Concentration mg/kg (mean)	Range mg/kg	Comments	Reference
Canada	Various	Till	Variable	140	9 - 1430	Till data from geological surveys conducted by the GSC. <63 µm size fraction. Aqua regia digestion and analysis by ICPMS or ASS. N=7397, SD=125.	Grunsky 2010
Ecoregions across Canada	2007	Overburden Soils	-	700	MDL – 4600	Analysis by INA	Garrett 2007.
North America (Manitoba is the only Canadian data included)	2005	-	0-5cm A-horizon C-horizon O-horizon	532 530 553 256	-	-	USGS 2005.
New Brunswick Fredericton East Saint John West Saint John	1997	Garden Soils	-	344 ± 9 (n=2) 276 ± 28(n=18) 302 ± 25 (n=4)	-	HNO ₃ / H ₂ O ₂ /HCl ICP-MS	Pilgrim and Schroeder 1997.
Nova Scotia Sydney	2001	Surface soils	0-30cm	65.9	22-590	Urban reference area concentrations north of coke ovens	JDAC Environmental Ltd./PWGSC 2001.
Quebec St. Lawrence Lowlands Appalachians Grenville Superior and Rae Labrador Trough	2010	Regional Background Soil Quality Estimates	-	200 265 200 200 245	-	-	Quebec Soil Protection and Contaminated Sites Rehabilitation Policy (MDDEP 2010)
Québec Chibougamau	1999	Surface Soils	-	61.8 (n=1244)	6 - 888	HNO ₃ /HCl/ICP	CCME 1999.
Ontario				72			
Quebec				62			
Quebec and Ontario	1999	Rural locations	-	67	-	HNO ₃ /HCl/ICP or AAS	CCME 1999.
Ontario Regions of Durham and York	2009	Baseline soil concentration (max, UCLM or MDL)	-	89.07	-	-	Jacques Whitford Ltd. 2009.
Ontario Ottawa	2001	Garden soil Street dust	NA	766 576	609 – 903 153 – 714	Samples were analysed by ICP-MS. The Ba detection limit = 1 mg/kg.	Rasmussen <i>et al.</i> 2001.
Ontario	1997	Agricultural All other land uses		190 210	-	Background Soil Quality Estimates	OMOE 1997.
Ontario	1993	Old urban parkland Rural Parkland		72 72	19-290 16-205	HNO ₃ /HCl/ICP/AA Detection limit 0.5 mg/kg	OMEE 1993.
Ontario Ottawa	-	Agricultural Clay Loam	Field 1: 0-20cm Field 2: 0-20cm Field 1: 50-65cm Field 2: 50-65cm	1022±312 912±148 995±55 914±22	830-1900 880-1100	HClO ₄ /HNO ₃ ICP/AE	Wang 1994 <i>pers com.</i>

Location	Year	Soil type	Sample Depth	Concentration mg/kg (mean)	Range mg/kg	Comments	Reference
Ontario Holland Marsh	1974	Surface Subsurface		269 309.2	252-285 293-330	IPAA	Chattopadhyay and Jervis 1974.
Ontario Southern Ontario (from Sault Ste. Marie southwards)	-	Surface Soils	0-25cm	730 ± 248	250-1800	Soil concentrations were considered representative of parent material or atmospheric deposition.	Garrett 1995 <i>pers com.</i>
Manitoba Flin Flon Creighton Bakers Narrows Provincial Park Cranberry Portage	2007	Publically accessible lands (boulevards, parks, playgrounds, schoolyards, vacant lots and undeveloped land)	-	77 (n=93) 44.6 (n=13) 103 (n=1) 59 (n=1)	-	Maximum value for all locations was 194 mg/kg.	Manitoba Conservation 2007.
Manitoba City of Thompson	2003	Schoolyards, parks, playgrounds and residential properties	0-2cm	47	17-99	-	Jones and Phillips 2003.
Manitoba North : (<i>JenPeg,</i> <i>Snow Lake, FlinFlon,</i> <i>Gillam, James Lake,</i> <i>Snow Lake,</i> <i>Thompson - Orr</i> <i>Lake</i>), Central: (<i>Minitonas,</i> <i>Swan River, The</i> <i>Pas</i>) South: (<i>Mediation</i> <i>Lake, Manitoba</i> <i>Escarpment, Pine</i> <i>Falls</i>)	-	-	North 0-5cm (organic) 5-10cm (clay/silt) 10-15cm (clay/silt) 15-30cm (clay/silt) Central 0-12cm (organic) 12-25cm (clay/silt) South 0-2cm (organic) 2- 15cm(clay/silt, sand) 17-22cm (sand)	92 48 37 106 114 112 239 136 93			Jones 2004 <i>pers com.</i>
Manitoba, Saskatchewan, Alberta	1999	Agricultural soils	0-20cm	662±170	120-4300	HF/HClO ₄ /HNO ₃ INAA. An increasing concentration trend from east to west through the Prairies was evident; however, lower concentrations became more prevalent in western Alberta	Garrett 2004 <i>pers com</i> ; CCME 1999.
Prairie Provinces	1999	Rural locations		662	-	HF/HClO ₄ /HNO ₃ (more aggressive digestion)	CCME 1999
Alberta Southwestern Alberta	2003 Not provided	Two background samples in clay till	-	281 and 224	-	Strong acid digestion, n=1128 Digestion by strong acid	AENV 2009a. AENV 2009a.
Alberta		-	-	325	-		

Location	Year	Soil type	Sample Depth	Concentration		Comments	Reference
				mg/kg (mean)	Range mg/kg		
						digestion, n=1129, mean is used as provincial background	
Alberta	-	Agricultural soils	0-15cm	253	52-690		
			15-30cm	256	66-730		
			30-60cm	263	53-1000		
			60-100cm	289	72-850	HNO ₃ /AA	Lutwick 1994 <i>pers com.</i>
Alberta	-	Rural Parkland Soils	0-5cm	241	170-290		Dinwoodie 2004 <i>pers com.</i>
Alberta	-	Rural Parkland Soils	5-15cm	247	150-300	HNO ₃ /HClO ₄ /AA	<i>pers com.</i>
British Columbia							
Vancouver Island				300			
Lower Mainland				300			
Greater Vancouver				150			
Southern Interior				350			
Kootenay				400			
Cariboo		Regional		300			
Skeena		Background Soil		400			
Omineca Peace	-	Quality Estimates	-	600	-	-	BCMWLAP 2010.
British Columbia							
Trail	1991	Sandbox soils		110±55.1	38.1-305	HNO ₃ /HClO ₄ /HCl	
		Park soils		117.2±53.9	56.4-341	ultrasonic	
		Residential soils	-	208.8±85.9	67-436	nebulisation-ICP	Kelly <i>et al.</i> 1991
		Before Incinerator:					
		1987		116			
		After incinerator:					
		1988		98			
British Columbia	1989			102			
Greater Vancouver	1990		-	121	-	HNO ₃ /HClO ₄ /ICP	Soilcon 1987-1990.
British Columbia							
Trail				180		HNO ₃ /HClO ₄	
Nelson	1980	Residential soils	0-2.5cm	182		ICP/AES	
Trail				1010		HF/HNO ₃ /HClO ₄	Lynch <i>et al.</i>
Nelson				908	-	ICP/AES	1980.
Spain							
Barcelona	2009	Habour site	-	565 ± 28	-	Road dust study. High concentrations of barium were associated with zones with braking activities.	Amato <i>et al.</i> 2009.

Notes:

- AA-Atomic Absorption; AE- Atomic Emission; ICP-Inductively Coupled Plasma; INAA-Instrumental Neutron Activation Analysis; IPAA- Instrumental Photon Activation Analysis; NR-Not Reported
- The method of digestion strongly influences the results of analysis of barium in soils. While *aqua regia* (HNO₃/HCl) releases the "biologically-relevant" barium contained in soluble salts and organic matter, the barium adsorbed onto soil particles as well as the barium present in some weak silicates, hydrofluoric acid (HF) also leaches barium from most silicates and stable mineral matrices (R. Garrett 2004, NRCAN, pers. com.). For example, Fox (1990) obtained recoveries of 17%, 30% and 80-98% barium from leaches of HNO₃/HCl, HNO₃/HClO₄ and HF/HCl/HNO₃/HClO₄, respectively. OMEE laboratories recovered an average of 20% (4-34%) of the barium contained in Canadian reference samples after HNO₃/HCl digestion of samples (L. Pastorek, OMEE, pers. com.).

Surface Water

Location	Year	Sample Depth	Concentration		Comments	Reference
			µg/L (mean)	Range µg/L		
Canada						
Atlantic				20-1000		
Central				50-70		
Western	Up to			<20-2200	Data is from the	
Pacific	1985		-	<100	NAQUADAT (1985) database.	CCREM 1987.
Ontario						
Durham Region	2009		89.3 (baseline)	-	-	Jacques Whitford Ltd. 2009.

Location	Year	Concentration µg/L (mean) concentration; max, UCLM or MDL)	Range µg/L	Comments	Reference
Ontario	1994-2003	26.3	20.2-50.3	Analysed using methods E3391A and E3386A.	Boyd 2004 <i>pers com.</i>
Ontario Lakes	1990-2002	28.6	5.2-591	Water collected at water treatment plant locations under Ontario Drinking Water Surveillance Program	Cheung 2004 <i>pers com.</i>
Ontario Rivers		25.2	5.95-65.1		
Ontario Tomoko Lake	1998	12.4 ± 0.2	-	-	Shuhaimi-Othman <i>et al.</i> 2006.
Restoule Lake		16.1 ± 1.2			
Nosbonsing Lake		8.3 ± 0.2			
Talon Lake		13.1 ± 0.9			
Great Lakes Dissolved barium	1988	-	18-53	Analyses were done using graphite-furnace atomic absorption spectrophotometry (GFAA) on 10 to 22 samples from each lake.	Rossmann and Barres 1988.
Barium in particulate fraction			0.025-5.3		
Total barium			18-52		
Manitoba Rural Northern lakes and rivers	-	-	4.6-8.7	-	Yee 2004 <i>pers com.</i>
Saskatchewan Rivers and streams	1998-2001	47	2-160	ICP-AES (Method 1728)	Hase 2004 <i>pers com.</i>
Lakes		18	1-82		
Alberta, Bow River Basin	1997-2003	76	10-219	Overall average for the 5 river basin was 91 µg/L	Anderson 2004 <i>pers com.</i>
Athabasca River Basin		90	7-389		
North Saskatchewan River Basin		78	31.6-506		
Oldman River Basin		110	30-271		
Red Deer River Basin		100	46-259		
British Columbia Quinsam River west of the Campbell River townsite	1990-1995	-	2-37.5	-	Regnier and Ryan 1998.
Thompson River at Spences Bridge			8-51		
South Thompson River at Kamloops			7-18		
Similkameen River near the U.S. border			18-119		
Columbia river at Birchbank			8-25		
Waneta			16.3-28		
Kootenay River at Fenwick			24-68		
Creston			16-50		
near the mouth of the Bonaparte River			22-78		
Salmon River at Hyder			25-620		
Fraser River at Marguerite			1.9-102		
Hope	15 to 97				

Groundwater

Location	Year	Concentration µg/L (mean)	Range µg/L	Comments	Reference
Prince Edward Island	1989	75	82-788	-	Jardine 1991 <i>pers com.</i>
Ontario	1990-2002	112.3	-	48 groundwater supply wells were sampled under the Ontario Drinking Water Surveillance Program.	Cheung 2004 <i>pers com.</i>
Ontario Western Lake Ontario	1993	109	94-197 (unpolluted samples)	Samples obtained from landfill leachate. Unpolluted evolving water samples and groundwater	Howard and Beck 1993.
Ontario Duffins Creek-Rouge River		-			

Location	Year	Concentration µg/L (mean)	Range µg/L	Comments	Reference
drainage basin			54-128 (contaminated samples)	samples contaminated with road de-icing chemicals were collected (n=20). No relationship was found between de-icing chemical contamination and barium levels. Variability was explained as the result of Ba sulphate dissolving in response to lower sulphate concentrations in pore water during transport through the soil.	Howard and Beck 1993.
Ontario Scarborough Bluffs upper aquifer in Toronto			90-302		
Don Valley urban pore waters	-	-	253-336		
Ontario - Sarnia Shallow (<15m)			60-510		
Deep (>15m)			210-300		
Very deep (>100m)	1991	-	71-100	-	Lesage et al. 1991.
Alberta Deep Wells		119	<10-1060	Deep wells (n=100) were analysed by method APHA 3120B. Shallow wells (n=111) were analysed by US EPA 200.8 method	Holt-Oduro 2004 pers com.
Shallow Wells	-	124	8-817		
British Columbia	-	20	0.7-230	Total (n=91) & dissolved (n=97) barium samples combined. High levels of barium can be found in groundwater due to leaching and eroding from sedimentary rock (WHO 1990) & coal.	Evans 2004 pers com.
British Columbia Proposed Coal Mine Site	1985	73000	1200-10 800		Buchanan 1985.
Yukon	1995-2001	59	<0.6-131	-	Beckerton 2004 pers com.

Drinking Water

Location	Year	Concentration µg/L	Range µg/L	Comments	Reference
Canada	2000	55 (mean)		Data collected as part of the 2000 Canadian Total Diet Study. 500mL tap water samples were collected	Dabeka 2004 <i>pers com.</i>
Canada		Median values		Sampled raw, treated & distributed drinking water serving appr. 36% of Canadian population. GFAA analysis.	
Prince Edward Island		-		Overall Cdn Ba concentrations (µg/L):	
Alberta		84	200-457	Raw ≤5-592 (median 16)	
Saskatchewan		33	56-213	Treated ≤5-576 (median 19)	
Ontario		24	28-70	Distributed ≤5-602 (median 18)	
New Brunswick		19	≤5-602	Barium levels in raw water were not significantly different from those in treated water (HC 1990).	Subramanian and Méranter 1984.
Manitoba		18	≤5-28		
British Columbia		≤5	≤5-32		
Nova Scotia		≤5	≤5-127		
Quebec		≤5	≤5-91		
Newfoundland	1984	≤5	≤5-51-		
Newfoundland	2000-2009	27.0 (mean)		N=7932, SD=68.0	GNL 2009.
		60 (arith. mean)		29% of the samples were below the detection limit of 10 µg/L. n=1147	Riopelle 1994 <i>pers com.</i>
Quebec	1992-1994	21 (geo. mean)	<10-1600		
		20 (median)			

Location	Year	Concentration µg/L	Range µg/L	Comments	Reference
Quebec Appalachians St. Lawrence Lowlands	1974-1982	Geometric mean values 41.5 192.5	-	Extensive sampling completed (+12 000 samples from Appalachian region). Samples primarily analysed by atomic absorption, resulting in a less sensitive detection limit which affects the degree of confidence in the lower percentiles of the reported distributions.	Choiniere and Beaumier 1997.
Ontario	1998-2007	40.9 (mean)		n=3695, SD=58.2	OMOE 2010.
Ontario Groundwater Lakes Rivers All sources	1990-2002	Mean values 111.84 26.39 24.03 54	-	Overall average was 54 µg/L for all sources. Groundwater n=989 (from 48 supply wells). Lake water n=2864 (from 84 treatment plants) and River water n=2221 (from 47 treatment plants).	Cheung 2004 <i>pers com.</i>
Manitoba Rural Northern groundwater wells treatment plants	-	-	7.3-37.4 9.2-9.9	Well water n=8 and treatment plant water n=3. Approximately 90% of the samples had concentrations below 100 µg/L.	Yee 2004 <i>pers com.</i>
Manitoba Rural communities	2001	-	<1-220		Yuen and Zimmer 2001.
Saskatchewan	2000-2009	47.1 (mean)		n=2517, SD=80.6	GS 2008.
Yukon	1999-2003	-	<20-169	n=57	Bergsam 2004 <i>pers com.</i>
United States	1972	43 (mean)	1.7-380	Data representative of municipal waters in the U.S.	Schroeder <i>et al.</i> 1972.

Sediment

Location	Year	Concentration mg/kg dw	Range mg/kg dw	Comments	Reference
Eastern Canada Bay of Fundy	1979	310	150-540	Generally barium is more associated with fine grained sediments (400 µg/g) than coarse grained sediments such as sand (290 - 300 µg/g).	Loring 1979.

					<p>Limitations to this data include variations in materials analysed (sediment, soil) and differences in analytical methods over time. Samples collected up until the early 1980's were analysed by atomic absorption. This technique was gradually replaced with plasma-atomic emission spectrometry (ICP-AES) resulting in a more sensitive detection limit and a higher degree of confidence in the lower percentiles of reported distributions</p>	Choiniere and Beaumier 1997.		
Quebec								
Appalachians		-	21.4-114.7					
St. Lawrence Lowlands		-	85.8-115.8					
Grenville		-	33-61.2					
Upper and Rae		-	50.7-97.8					
Labrador Trench	1967-1997	89.1	-					
78.59 (baseline concentration; max, UCLM or MDL)								
Ontario								
Durham Region	2009		-	-		Jacques Whitford Ltd. 2009.		
Ontario								
Tomiko Lake		20.5 ± 1.8						
Restoule Lake		21.3 ± 2.2						
Nosbonsing Lake		26.8 ± 1.5						
Talon Lake	1998	74.9 ± 3.8	-			Shuhaimi-Othman <i>et al.</i> 2006.		
Manitoba								
Northern lakes and rivers	-	-	21.2-56.3	n=5		Yee 2004 <i>pers com.</i>		
Medians								
Yukon								
Cassiar Platform		814 (n=25 739)						
Insular		820 (n=2306)						
Intermontane		538 (n=399)						
North American Shelf		920 (n=2324)						
Northern Shelf		620 (n=4732)						
Selwyn Basin		600 (n=937)						
Triass-Cretac		920 (n=4619)						
Tanana Terrane	2003	465 (n=1837)	-					
		870 (n=7472)				Heon 2003.		

Biota Used as Human Food

Location and Type of Food	Year	Concentration mg/kg dry weight (mean)	Range mg/kg dw	Comment	Reference
Newfoundland Crab tissue (male Atlantic snowcrab, queen crab and spider crab) Inner Avalon Bay St. George Outer Avalon Bonavista White Bay Conception Bay Shoal Patch Port au Choix			0.16-5.48 (n=23) 0.1-17 (n=30) 0.09-8.88 (n=36) 0.05-5.03 (n=24) 0.08-17.7 (n=24) 0.08-14.7 (n=36) 0.11-12.1 (n=24) 0.05-10.2 (n=29)	Tissue analyses were conducted by inductively coupled plasma mass spectrometry (ICP/MS) and metal concentrations were reported in µg metal/g tissue (dry weight). The Ba detection limit was 0.01 µg/g. The maximum detected barium concentration consistently occurred in the crab gills. Note that data provided for both crabs and clams had a greater frequency of occurrence of lower range concentrations compared to high concentrations.	
Clam tissue (Arctic surfclam) sampled at Banquereau Bank	1996		0.14-3.34		Fancey 2004 <i>pers com.</i>
		0.0979 (foot) 7.9 (digestive gland) 1.1 (kidney) 0.14 (gills) 0.38 (mantle)			
Newfoundland, Bellevue <i>Mytilus edulis</i> (mussels)	-		-	-	Lobel <i>et al.</i> 1991.
Nova Scotia <i>Mytilus edulis</i> (blue mussels)	-	0.583 (wet wt)	0.1-1.6 (wet wt)		Duerden 1991 <i>pers com.</i>
Northwest Atlantic Cod	-	-	0.02-0.1 (one stock) 0-0.02 (another stock)	Samples were analysed using ICP-MS.	Hellou <i>et al.</i> 1992.
Durham Region, Ontario Fruit Chicken Beef Pork Dairy Egg Crop Fish	2009	(baseline concentration; max, UCLM or MDL) 0.74 0.402 0.065 0.061 0.05 0.398 0.034 2.31	-	-	Jacques Whitford Ltd. 2009.
Manitoba - Northern rural gardens: Radishes Potatoes Carrots Turnips Strawberries Blueberries Mossberries	-	18.2 0.58 22.2 17 11.8 11.4 7.15	-	Note that these concentrations were determined on a dry weight basis and are relatively higher than those determined (on a wet weight basis) in the 2000 Total Diet Study. It is unknown if produce was washed prior to analysis.	Yee 2004 <i>pers com.</i>
British Columbia: 54 uncontaminated lakes Rainbow trout Cutthroat trout Lake trout	-	Liver Tissue 0.32±0.22 (n=110) 0.29±0.22 (n=75) 0.28±0.09 (n=19)	Muscle Tissue 0.24 (n=112) 0.22±0.02 (n=54) 0.25±0.08 (n=25)	Concentrations are expressed as wet weight.	Rieberger 1992.

Location and Type of Food	Year	Concentration mg/kg dry weight (mean)	Range mg/kg dw	Comment	Reference
Dolly Varden		0.26 (n=49)	0.23±0.05 (n=51)		
Mountain Whitefish		0.26 (n=24)	0.33±0.27		
Arctic Grayling		0.22±0.04 (n=13)	0.24 (n=22)		
British Columbia – four unpolluted nearshore locations				The study concluded that there were no significant differences in Ba concentrations in marine benthic animal tissues between the four study areas.	Environment Canada 1987, 1988.
Fish muscle		-	<0.08-0.71		
Eel pout muscle		-	1.81-5.02		
Shrimp		-	Up to 3.1		
Blue mussel		1.4	0.6-3.7		
Yoldia mussels	1987-1988	18.07	9.8-25.10		
British Columbia <i>Pandalus platyceros</i> (spot prawn)				Samples collected from abdomen tissues.	Whyte and Boutillier 1991.
	-	-	0.11-2.27		

Note: Food data is preferably obtained at wet weight; however, for some of the table entries above, only dry weight was available.

Commercial Foods

Food Type	Year	Concentration	Range	Comment	Reference
Formula Milk Based Soy-based	2000	35 µg/L 129 µg/L (mean)	<45-47 ng/g (n=2) 125-135 ng/g (n=2)	Density was assumed to be 1 g/mL. Results were part of 2000 Canadian Total Diet Study.	Dabeka 2004 <i>pers. com.</i>
Bottled Water Mineral Water Reverse Osmois/Distilled Water Spring Water Mineral Water.	1995- 1996	(mean) 211 µg/L (n=42) 0.42 µg/L (n=25) 65 µg/L (n=102) 8.2 µg/L (n=19)	-	All samples were within the WHO guideline of 700 µg/L for mineral water; although, one Canadian mineral water sample (662 µg/L) approached this guideline. All samples complied with the Canadian guideline of 1 mg/L.	Dabeka <i>et al.</i> 2002.
Long term dietary intake for four individuals	1990	0.9 mg/d	0.44-1.8 mg/d	Reported for food and fluid	Health Canada 1990.
Average Intake via Food U.S. hospitals England Japan	1988	750 µg/day 603 µg/day (SD=225) 450 µg/day	300-1770 µg/day		Stanek <i>et al.</i> 1988.
Food intake	-	-	<303-1700 µg/day	Values apply to 70kg adult	Reeves 1986, WHO 1990 and ATSDR 1992.
Preschooler food intake	1988	266 µg/day (arithmetic mean) 207 µg/day (median)	12.5-14,400 µg/day	Study of 64 U.S. preschoolers (1-4 yrs). Intakes measured by ICP-AES based on 6 daily collections per child.	Stanek <i>et al.</i> 1988

Human Tissues and Biological Fluids

Tissue/Fluid	Year	Concentration (mean)	Range	Comment	Reference
Total body (70kg male)	-	22 mg	-	Total body burden of barium with the major portion (93%) concentrated in bone and connective tissue.	Tipton <i>et al.</i> 1963; Schroeder <i>et al.</i> 1972; ICRP 1974; Schroeder 1970; NAS 1977
Bone	1957	-	7-8.5 µg/g	-	Sowden and Stitch 1957.
Lungs		0.16 µg/g			
Connective tissue		0.125 µg/g			
Skin		0.057 µg/g			
Bone		2 µg/g			
Adipose tissue	1972	0.036 µg/g	-		Schroeder <i>et al.</i> 1972.
United States					
Pancreas		1.5 µg/g in ash			
Kidney		1.2 µg/g in ash			
Brain		<0.2 µg/g in ash			
Liver		<0.2 µg/g in ash			
Aorta		7 µg/g in ash			
Spleen		0.5 µg/g in ash			
Heart		0.7 µg/g in ash			
Testi		1 µg/g in ash			
Lung	1965	13 µg/g in ash	-		Tipton <i>et al.</i> 1965.
Blood	1975	-	80-400 µg/L		Goody <i>et al.</i> 1975.
Maternal blood		87 µg/L		Analysed using emission spectroscopy.	
Cord blood		100 µg/L			
Placental blood	1976	101 µg/L	-		Creason <i>et al.</i> 1976.
Urine Excretion	1969	-	17-37 µg/day		Tipton <i>et al.</i> 1969.
United States					
Tooth enamel	1974	4.2 µg/g dry wt	-	American subjects under the age of 20.	Losee <i>et al.</i> 1974.
International					
Tooth enamel	1979	22 µg/g dry wt	-	Subjects from 13 countries (including the U.S) under the age of 20.	Cutress 1979.
Scalp hair		2.5 µg/g (n=61)	1-2 µg/g		Creason <i>et al.</i> 1975; 1976
Pubic hair	1975-76	2.2 µg/g (n=110)			
Scalp hair (children)			1.4-2.9 µg/g (n=122)	Subject resided in three Alberta First Nation villages. Analysis was by ICP-ES.	
Scalp hair (adults)	1986		1.3-1.7 µg/g (n=27)		Moon <i>et al.</i> 1986.
Hair (patients with multiple sclerosis)				Pathological conditions can alter the barium concentration in human hair and blood	
Hair (control, no MS)					
Blood (patients with multiple sclerosis)		3.37 ± 2.92 µg/g			
Blood (control, no MS)	1985	1.68 ± 0.713 µg/g	-		Ward and Bryce-Smith 1985.
Primary Teeth		144 ± 19 µg/L			
Drinking water >10 000 µg Ba/L		126 ± 22 µg/L			
Drinking water <100 µg Ba/L	1984	28.3 µg/g	-	Exposure to higher barium levels in the environment can also increase barium uptake.	Curzon <i>et al.</i> 1984.
Whole Blood		10.4 µg/g		Healthy volunteers. Analysis was completed by multi-element inductively coupled plasma mass spectrometry (ICP-MS).	
Plasma		Median	5 th -95 th percentile		
Urine		59 mg/L (n=100)	46.4-77.6 mg/L		
Hair		111 mg/L(n=100)	90-154 mg/L		
		0.89 mg/L (n=100)	0.17-3.85 mg/L		
		0.28 mg/L(n=45)	0.05-1.58 mg/L		Goullé <i>et al.</i> 2005.

Rain, Snow and Fog

Location	Year	Concentration (mean)	Range	Comments	Reference
Ontario Snow Simcoe County Old Johnson Farm (2 sites) Parnell Farm	2009	0.88 ± 0.45 ng/L 1.3 ± 1.6 ng/L 1.7 ± 0.6 ng/L	-	Results based on 3 samples per location.	Shotyk <i>et al.</i> 2010. Wagner 1991 <i>pers. com.</i>
Ontario Precipitation	-	2.3 µg/L	1.45-3 µg/L	-	-
Antarctic Snow	1998-2002	2.4 pg/g (mean)	-	Study involved 46 snow samples from a 2.3 m snow pit covering austral spring 1998 to summer 2002. Metal concentration obtained by analysing large size snow blocks collected from clean snow pits at two remote sites in Coats Land, Antarctica. Analyses performed with ultra sensitive inductively coupled plasma sector field mass spectrometry (ICP-SFMS) technique. Natural contributions (rock, soil dust, seasalt spray, volcanic emissions) and anthropogenic sources (non-ferrous metal mining) were identified.	Do Hur <i>et al.</i> 2007.
Antarctic Snow	1920s-1990s	2.5 pg/g (mean based on 81 depth intervals)	-	Analysis completed by ICP-SFMS. Samples from various sections of a dated snow/ice core drilled at 6542 m altitude. Ba concentrations display pronounced variations with depth and to differ by orders of magnitudes from Antarctic's studies. The results showed the evidence of metal pollution associated with human activity in South America.	Planchon <i>et al.</i> 2002.
Bolivia, Sajama Ice Cap Snow/ice	2004	9465.85 pg/g	1200-52 000 pg/g		Hong <i>et al.</i> 2004.
Finland, Norway and Russia Rainwater	1997	-	0.47-1.07 µg/L (median range)	Analysis by ICP-MS.	Reimann <i>et al.</i> 1997.

Appendix 2. Yearly Average Intake of Barium via Food Ingestion (Weight-adjusted)

Barium (Ba)	0-6mo M&F	7mo-4yrs M&F	5-11yrs M&F	12-19yrs M&F	20+yrs M&F
2000	16.42	19.24	14.90	8.24	6.26
2001	21.97	23.76	17.71	9.99	7.90
2002	20.79	18.93	14.49	8.10	5.84
2003	18.50	21.06	15.59	8.43	6.18
2004	16.81	19.23	14.72	8.19	6.30
2005	15.82	20.13	16.05	8.97	6.71
2006	23.48	24.74	18.50	10.38	8.36
2007	21.92	24.53	18.97	10.71	8.41
Mean	19.46	21.45	16.37	9.13	7.00
Standard Deviation	2.95	2.50	1.78	1.07	1.05

Notes:

- Reference: Robert Dabeka *et al.* 2010. - Above values were applied to non-breast-fed infants for the purposes of calculating EDIs for infants (birth to 6 months). Breast milk concentrations were used to calculate the EDI for breast-fed infants.

Appendix 3. Typical Environmental Concentrations Used in EDI Calculations

Media	Units	Distribution	Statistics	Barium
Drinking Water ¹	µg/L	Lognormal	Arithmetic Mean	34.19
			Standard Deviation	68.56
			z	3
			Minimum	0
			Maximum	690
Outdoor Air ²	µg/m ³	Lognormal	Arithmetic Mean	0.00192
			Standard Deviation	0.00319
			z	3
			Minimum	0
			Maximum	0.03
Indoor Air ³	µg/m ³	Lognormal	Arithmetic Mean	0.00267
			Standard Deviation	0.00424
			z	3
			Minimum	0
			Maximum	0.04
Soil ⁴	mg/kg	Lognormal	Arithmetic Mean	140
			Standard Deviation	125
			z	3
			Minimum	0
			Maximum	1038
Settled Dust ⁵	mg/kg	Lognormal	Arithmetic Mean	305.27
			Standard Deviation	311.25
			z	3
			Minimum	0
			Maximum	2691
Breast Milk ⁶	µg/L	Lognormal	Arithmetic Mean	3.61
			Standard Deviation	8.67
			z	3
			Minimum	0
			Maximum	88

¹ Based on average barium concentrations of drinking water from Ontario (1998-2007), Saskatchewan (2000-2009) and Newfoundland and Labrador (2000-2009) (Health Canada 2011).

² Outdoor air PM_{2.5} concentrations NAPS data collected from 2003 to 2009 from British Columbia, Ontario, Quebec and New Brunswick from urban and rural centers (Health Canada 2011).

³ Indoor air concentrations based on PM_{2.5} from Graney *et al.* (2004) and Alberta Health (1998) (Health Canada 2011).

⁴ Based on Geological Survey of Canada data (Grunsky 2010, Health Canada 2011).

⁵ Based on arithmetic mean of total barium in indoor settled dust from (Rasmussen *et al.* 2001) and NHEXAS (Health Canada 2011).

⁶ Based on barium concentration in breastmilk for various literature sources: Friel *et al.* (1999), Krachler *et al.* (1998), Krachler *et al.* (1999), Coni *et al.* (1990), Coni *et al.* (2000) and Abdulrazzaq *et al.* (2008) (Health Canada 2011).

Appendix 4. Receptor Characteristics of the Canadian General Population¹

	Statistic	Breast fed Infant (0 to 6 mo.)	Non-Breast fed Infant (0 to 6 mo.)	Toddler (7 mo. to 4 yr)	Child (5 to 11 yr)	Teen (12 to 19 yr)	Adult (20+ yr)
Body Weight (kg)	Minimum	2.8	2.8	7.1	14.2	30.0	38.1
	Maximum	21.5	21.5	35.9	71.5	112.2	126.5
	Mean	8.2	8.2	16.5	32.9	59.7	70.7
	Std. dev.	2.9	2.9	4.5	8.9	13.5	14.5
	Distribution	Lognormal	Lognormal	Lognormal	Lognormal	Lognormal	Lognormal
Skin Surface Area Hands (cm ²)	Minimum	242	242	299	396	556	614
	Maximum	416	416	614	863	1142	1262
	Mean	320	320	430	590	800	70.7
	Std. dev.	30	30	50	80	100	14.5
	Distribution	Lognormal	Lognormal	Lognormal	Lognormal	Lognormal	Lognormal
Skin Surface Area Arms (cm ²)	Minimum	200	200	396	797	1409	1588
	Maximum	1367	1367	1882	2645	3465	3906
	Mean	550	550	890	1480	2230	2510
	Std. dev.	180	180	240	300	340	360
	Distribution	Lognormal	Lognormal	Lognormal	Lognormal	Lognormal	Lognormal
Skin Surface Area Legs (cm ²)	Minimum	539	539	907	1604	3042	3753
	Maximum	1496	1496	3012	5655	7945	8694
	Mean	910	910	1690	3070	4970	5720
	Std. dev.	160	160	340	660	810	760
	Distribution	Lognormal	Lognormal	Lognormal	Lognormal	Lognormal	Lognormal
Soil Loading to exposed skin ² Hands Surfaces other than hands (kg/cm ² /event)	Mean	1.0 x 10 ⁻⁷ 1.0 x 10 ⁻⁸	1.0 x 10 ⁻⁷ 1.0 x 10 ⁻⁸	1.0 x 10 ⁻⁷ 1.0 x 10 ⁻⁸	1.0 x 10 ⁻⁷ 1.0 x 10 ⁻⁸	1.0 x 10 ⁻⁷ 1.0 x 10 ⁻⁸	1.0 x 10 ⁻⁷ 1.0 x 10 ⁻⁸
Time spent ³ outdoors (hr/d)	Minimum	0.000	0.000	0.000	0.000	0.000	0.000
	Maximum	3	3	3	4	9.45	10.76
	Mean/Mode	1.25	1.25	1.25	2.2	1.42	1.43
	Std. dev.	N/A	N/A	N/A	N/A	1.17	1.28
	Distribution	Triangular	Triangular	Triangular	Triangular	Triangular	Lognormal

¹Mean receptor characteristics from Richardson (1997) and CCME (2006) unless otherwise stated.

²Soil loadings from Kissel *et al.* 1996, 1998 as referenced in CCME (2006).

³Time spent outdoors by infant, toddler or child is assumed to be equivalent to that of an adult if child or infant is assumed to be accompanied by an adult.

Appendix 5. Typical Values for Intakes of Air, Water and Soil by the Canadian General Population¹

<i>Intake rates</i> ¹	<i>Statistic</i>	<i>Breast fed Infant (0 to 6 mo.)</i>	<i>Non-Breast fed Infant (0 to 6 mo.)</i>	<i>Toddler (7 mo. to 4 yr)</i>	<i>Child (5 to 11 yr)</i>	<i>Teen (12 to 19 yr)</i>	<i>Adult (20+ yr)</i>
Air inhalation (m ³ /d)	Minimum	1.1	1.1	4.6	8.3	9	9.5
	Maximum	4.4	4.4	15.6	25	28.9	33
	Mean	2.18	2.18	8.31	14.52	15.57	16.57
	Std. dev.	0.59	0.59	2.19	3.38	4.00	4.05
	Distribution	Lognormal	Lognormal	Lognormal	Lognormal	Lognormal	Lognormal
Water Ingestion ² (L/d)	Minimum	N/A	0.1	0.2	0.2	0.2	0.2
	Maximum	N/A	0.7	0.9	1.1	2	2.7
	Mean	N/A	0.3	0.6	0.8	1	1.5
	Std. dev.	N/A	0.2	0.4	0.4	0.6	0.8
	Distribution	N/A	Lognormal	Lognormal	Lognormal	Lognormal	Lognormal
Soil Ingestion ³ (kg/d)		2.0 x 10 ⁻⁵	2.0 x 10 ⁻⁵	8.0 x 10 ⁻⁵	2.0 x 10 ⁻⁵	2.0 x 10 ⁻⁵	2.0 x 10 ⁻⁵
Soil Inhalation ⁴ (m ³ /d)		1.66 x 10 ⁻⁹	1.66 x 10 ⁻⁹	6.32 x 10 ⁻⁹	1.10 x 10 ⁻⁸	1.10 x 10 ⁻⁸	1.26 x 10 ⁻⁸
Indoor Settled Dust Ingestion (kg/d)	Minimum	8.0 x 10 ⁻⁸	8.0 x 10 ⁻⁸	0.00	0.00	0.00	0.00
	Maximum	1.77 x 10 ⁻³	1.77 x 10 ⁻³	9.4 x 10 ⁻⁴	8.33 x 10 ⁻⁴	3.39 x 10 ⁻⁵	6.20 x 10 ⁻⁵
	Mean	3.74 x 10 ⁻⁵	3.74 x 10 ⁻⁵	4.06 x 10 ⁻⁵	3.17 x 10 ⁻⁵	2.07 x 10 ⁻⁶	2.51 x 10 ⁻⁶
	Std. dev.	8.33 x 10 ⁻⁵	8.33 x 10 ⁻⁵	5.22 x 10 ⁻⁵	4.58 x 10 ⁻⁵	2.32 x 10 ⁻⁶	3.06 x 10 ⁻⁶
	Distribution	Lognormal	Lognormal	Lognormal	Lognormal	Lognormal	Lognormal
Food ⁵	Minimum	0.5	5.590	0.000	0.000	0.000	0.000
	Maximum	1	19.475	23.981	17.744	10.667	8.323
	Mean/Mode	0.7	12.533	11.142	8.148	4.956	3.945
	Std. dev.	N/A	2.314	4.280	3.199	3.945	1.459
	Distribution	Triangular	Lognormal	Lognormal	Lognormal	Lognormal	Lognormal

¹ Probability distribution function curves for receptor intake rates from Health Canada (2011) unless otherwise stated.

² Breast fed infants are assumed to be exclusively breastfed for 6 months and are not given drinking water. Infants that are not breastfed are assumed to consume 0.3L of drinking water based on HC 2004.

³ Soil ingestion rates from CCME (2006).

⁴ Soil inhalation rates based on Allan et al.(2008) and a PM10 concentration of 0.76 µg/m3 (CCME 2006).

⁵ Breastfed infants are assumed to be exclusively breast fed for 6 months and non-breastfed infants are assumed to be fed a mixture of milk, formula and table food.

Appendix 6. Estimated Total Daily Barium Intake by Age Class for the Canadian General Population¹

Medium of exposure	Daily Barium Intake (µg/kg bw/day)					
	BF-Infant (0-6 mo)	NBF-Infant (0-6 mo)	Toddler (7mo- 4yr)	Child (5-11 yr)	Teen (12-19 yr)	Adult (20 yr+)
AIR						
Ambient Air (Inhalation)	0.000014	0.000014	0.000026	0.000034	0.000012	0.000010
Indoor Air (Inhalation)	0.00036	0.00036	0.00067	0.00058	0.00034	0.00031
DRINKING WATER						
Drinking Water (Ingestion)	NA	0.49	0.43	0.30	0.21	0.28
INDOOR SETTLED DUST						
Settled Dust (Ingestion)	0.43	0.43	0.34	0.12	0.0050	0.0049
Settled Dust (Dermal)	0.13	0.13	0.091	0.070	0.055	0.0053
SOIL						
Soil (Ingestion)	0.27	0.27	0.53	0.067	0.036	0.030
Soil (Inhalation)	0.0000012	0.0000012	0.0000022	0.0000028	0.0000094	0.0000083
Soil (Dermal)	0.063	0.063	0.045	0.034	0.027	0.026
FOOD						
Food (Ingestion)	0.13	19	21	16	9.0	6.8
TOTAL						
TOTAL EDI*	1.4	22	24	17	9.5	7.4

¹ Median values of estimated daily intake values for each age class were modelled based on receptor characteristics details listed in Appendix 4 and 5 and the probability distribution functions of typical concentrations of air (indoor and outdoor), drinking water, indoor settled dust, soil and food based on details in Appendix 3. The probabilistic modelling of the EDI was completed as described in Health Canada (2011 Draft). The median value (50th percentile) was chosen to represent the EDI values for the Canadian population.

* Since a probabilistic method was used to develop the EDIs, the total EDI is not the sum of all sub-EDIs for each age category. The total EDI and each sub-EDI have individual probability distribution functions. The 50th percentile (median) for each distribution is displayed in the above table.

Appendix 7. Typical Values for Average Body Weights and Intakes of Air, Water and Soil by the Canadian General Population used in SQG Calculation

Age (years)	Body weight¹ (kg)	Air intake² (m³/d)	Water intake¹ (L/d)	Soil intake¹ (g/d)	Soil inhalation^{3,4} (g/d)	Settled indoor dust ingestion⁵(g/d)
0-6 months	8.2	2.2	0.3	0.02	0.0000017	0.037
7 months - 4	16.5	8.3	0.6	0.08	0.0000063	0.041
5-11	32.9	14.5	0.8	0.02	0.000011	0.032
12-19	59.7	15.6	1.0	0.02	0.000012	0.0021
20+	70.7	16.6	1.5	0.02	0.000013	0.0025

¹ Health Canada 2010a and CCME 2006

² Allan *et al.* 2008/2009

³ Health Canada 2010a

⁴ Air intake (m³/d) x average airborne concentration of respirable particulate (0.00076 g/m³)

⁵ Wilson *et al.* (in press).