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Ministry of Environment

Derivation of Proposed 2007 Draft Matrix Soil Standards for Barium

Glyn R. Fox

Environmental Management Branch

Environmental Protection Division

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1. Introduction

Barium is used in a number of industries including: optical glass, paint and rubber manufacture, (Patty, 1981). Various barium compounds are also used in the electronic, friction materiel, pesticide, pharmaceutical, pyrotechnic and speciality paper industries (Alberta Environment, 2004a; CCME, 1999). Barite (barium sulphate) is the most commonly used barium mineral in industry. It has been estimated that between 80% (Energy, Mines and Resources Canada, 1993) and 95% (Patty, 1981) of the world's annual production of barite is used by the petroleum producing industry as a "weighting agent" in oil and gas well drilling mud compositions (Wikipedia, 2007).

The toxicity of barium *per os* is attributed to the barium ion (Ba^{+2}) and therefore, the toxicity of a particular barium compound is related to that compound's respective solubility (ATSDR, 2005; Dibello et al., 2003; US EPA, 1997; WHO, 1990). As shown in Table 1, the oral toxicity of barium compounds, as reflected by acute LD50 values in adult rats, tends to decrease commensurate with corresponding decreased water solubility.

However, Table 1 also shows that while both barium chromate and barium sulphate are virtually insoluble in water, barium chromate in contrast to barium sulphate retains some degree of toxicity. Thus, only barium sulphate is essentially non-toxic to rats (Boyd & Able, 1966)[1] and humans (ATSDR, 2005; US EPA, 1994) via the oral route of exposure. [2]

Although in general, the solubility of barium compounds increases with decreasing pH (ATSDR, 2005; WHO, 1991), barium sulphate is only very sparingly soluble in alcohol, alkalis and weak or dilute acids (Alberta Environment, 2004b; Merck & Co., 1976; Patty, 1981; US EPA, 1994). Consequently, the ministry recognizes that barite (barium sulphate) is unique among barium compounds in being demonstratively insoluble and non-toxic under most environmental conditions.

It is also recognized that use of the current Strong Acid Leachable Metals (SALM) in Soil (B.C. Ministry of Environment, 2007a) extractive analytical method can result in considerable over-estimation of soluble barium concentrations in soil containing barium sulphate when compared to more environmentally relevant extractive methods. Over-estimation of soluble barium attributable to barium sulphate in soil by the SALM method is of particular concern at oil and gas well sites where large amounts of barite is used.

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[1] Note that the toxic effects provoked by barium sulphate in the Boyd & Able, 1966 study were physical/mechanical (i.e. gastric fistula/fissure and intestinal occlusion) rather than chemical in nature.
[2] If inhaled, barite dust acts as a physical respiratory irritant and can cause associated inflammatory pulmonary disease e.g. baritosis, a benign pneumoconiosis (NIOSH, 1999).

To address this issue of extractive bias related to barium sulphate, the ministry with the assistance of the British Columbia Laboratory Quality Assurance Advisory Committee (BCLQAAC) has now developed a more environmentally appropriate chemical extractive method. The new Soluble Barium by Calcium Chloride Extraction method (BC Ministry of Environment, 2007b) is based on cation exchange associated extraction of soil rather than the more traditional strong acid digestive extraction used in the SALM method. Compared to the SALM, the new calcium chloride method is much less "aggressive" in its ability to extract barium from barite in soil. The new method however, is still able to ensure complete extraction of barium from other more soluble and therefore more toxic, barium compounds which may be present in soil.

Full details related to the development and validation of the calcium chloride method are presented in the following reports:

- Development of BC CSR Analytical Method for Soluble Barium, Phase 1: Evaluation of Viable Analytical Methods for Soluble Barium., Hugdahl et al., 2007a,

- Development of BC CSR Analytical Method for Soluble Barium, Phase 2: Optimization and Ruggedness Testing for Soluble and Total Barium Methods., Hugdahl et al., 2007b, and

- Development of BC CSR Analytical Method for Soluble Barium, Phase 3: Inter-laboratory Testing of the Analytical Methods for Soluble Barium and BC SALM Barium., Hugdahl et al., 2007c.

The new environmentally relevant calcium chloride extraction method for barium has been designed and validated strictly for use at barite sites.[3] At barite sites only, barium concentrations in soil may be determined using the Soluble Barium by Calcium Chloride Extraction method. For all sites other than barite sites, barium concentrations in soil must be determined using the Strong Acid Leachable Metals (SALM) in Soil method. Administrative rules related to determining if a site is barite site will be provided at a future date in the following Director's protocol:

- Director's Protocol 14, Requirements for Determining Barite Sites and Rules of Application for Soluble Barium by Calcium Chloride Extraction Analytical Method., (B.C. Ministry of Environment, 2007c).

[3] A barite site is a site at which it can be demonstrated to the satisfaction of the Director of Waste Management that the only form of barium used for commercial/industrial purposes at the site was barium sulphate.

Generic soil quality standards for barium are currently provided in Schedule 4 of the Contaminated Sites Regulation (British Columbia, 2005). The ministry with the assistance of the British Columbia Upstream Petroleum Environmental Committee, Barite-Barium Issues Technical Advisory Committee, (Appendix A) has now developed and is proposing for use under the Regulation, proposed 2007 draft matrix soil quality standards for barium.

2. Details Related to Derivation of 2007 Proposed Draft Matrix Soil Standards

This report provides details related to the derivation of the proposed 2007 draft matrix soil quality standards for barium presented in Exhibit 1.

The proposed 2007 draft standards were developed in accordance with the Contaminated Sites Standards Task Group (CSST) Procedures for the Derivation of Soil Quality Matrix Standards for Contaminated Sites, (B.C. Environment, 1996).

2.1 Derivation of Human Health Protection Standards – Intake of contaminated soil

Details related to the CSST, 1996 equations and parameter values used to derive human health protection - intake of contaminated soil, preliminary soil standards for barium are presented in Appendix B.

The US EPA (IRIS) Integrated Risk Information System oral reference dose (RfD_O) of 0.2 mg/kg/d for barium was used as the tolerable daily intake (TDI) in developing preliminary soil ingestion standards for barium. Scientific details related to the derivation of the US EPA, RfD_O for barium can be found in US EPA, 2005a; 2005b.

The ministry considers barium to be a threshold toxicant (i.e. a non-carcinogenic substance) by ingestion based on conclusions by the US EPA that, "adequate chronic oral exposure studies in rats and mice have not demonstrated carcinogenic effects" (US EPA, 2005a) and "barium is considered not likely to be carcinogenic to humans following oral exposure" (US EPA, 2005b).

To protect humans from inadvertent intake of barium contaminated soil, the following preliminary matrix soil standards were calculated:

Land use	**Preliminary standard (ug/g)**
Agricultural/Residential/Parkland	6,500
Commercial	19,697

2.2 Derivation of Human Health Protection Standards – Groundwater used for drinking water

Preliminary soil standards to protect human health from barium leaching from contaminated soil into groundwater used as a potable water source were derived in accordance with CSST, 1996 procedures. Under the CCST procedures, preliminary soil standards to protect drinking water from soil to water contaminant transfer are back-

calculated using the ministry's approved groundwater transport model (B.C. Ministry of Environment, 2006) and the Schedule 6 drinking water protective water quality standards of the Contaminated Sites Regulation (CSR). The CSR Schedule 6 drinking water standard for barium is 1,000 ug/L (British Columbia, 2005). The Schedule 6 drinking water standard was adopted directly from the Canadian Drinking Water Guidelines (Health Canada, 1990; 2007).

The following barium-specific parameter values were used in the groundwater transport model to back-calculate preliminary matrix soil standards to protect groundwater used for drinking water:

Kd: 100 L/kg
t: 2,200 years.

The dissociation constant (Kd) value of 100 L/kg for barium is based on an empirical study, Estimation of a Generic Adsorption Coefficient Kd for Barium, (Lintott and Tindal, 2007). The study authors recommended adoption of a Kd value of 100 L/kg for barium to the Barite-Barium Issues Technical Advisory Committee. The ministry in turn has accepted the recommendation of the Barite-Barium Issues Technical Advisory Committee to use a Kd = 100 L/kg in deriving barium matrix soil standards to protect various water uses, including use as drinking water.

A value of 2,200 years was used for the "time since contamination release" parameter (t) in back calculating a barium matrix soil standard to protect drinking water. This value of 2,200 years differs from the 100 years specified for parameter (t) in exhibit 7 of the CSST procedures (BC Environment, 1996). The value, t = 100 years listed in the CSST document is specific to organic substances. A value, t = 2,200 years is however, considered more appropriate for inorganic substances and has been consistently used by the ministry in back calculating matrix soil standards to protect various water uses for all other inorganic substances listed in Schedule 5 of the Contaminated Sites Regulation. Due to an editorial oversight, Exhibit 7 of the CSST, 1996 procedures only lists the value, t = 100 years, appropriate for use with organic substances.

Details of the other groundwater model parameter values used in the calculation of groundwater protective preliminary matrix soil standards for barium appear in Appendix D. [4]

To protect groundwater used as drinking water, a preliminary matrix soil standard of 331 ug/g, applicable to all land uses, was calculated.

[4] CSST, 1996 equations were used in calculating soil to groundwater protective standards.

2.3 Derivation of Environmental Protection Standards – Toxicity to soil invertebrates and plants

As an initial step towards developing matrix soil standards for barium, the ministry in 2005, had derived preliminary draft environmental protection soil invertebrate and plant protective matrix standards. These previously derived preliminary standards were based on soil invertebrate and plant toxicological data summarized in the companion scientific supporting document (Environment Canada, 1999) prepared for the Canadian soil quality guidelines for barium (CCME, 1999).

To ensure that any additional barium eco-toxicological data which may have become available since 1999 was included in the derivation of the 2007 draft matrix soil standards, the Barite-Barium Issues Technical Advisory Committee recommended that the 1999 to 2006 eco-toxicological literature be reviewed and all data to 2006 be compiled. Axiom Environmental Inc., under contract to the Ministry of Energy, Mines and Petroleum Resources, completed updating of the barium eco-toxicological database in their report; Updated Ecotox Database and Revised Ecological Direct Contact Soil Standard for Soluble Barium (Tindal, 2007).

The Tindal report, in addition to compiling the barium eco-toxicological data available to 2006, also derived preliminary soil standards using that extended database in accordance with CSST, 1996 procedures. To protect soil invertebrates and plants, the following preliminary soil standards were derived for soluble barium:

Land use	**Preliminary standard (ug/g)**
Agricultural/Residential/Parkland	1,218
Commercial	1,406

The ministry has reviewed the scientific defensibility of the above mentioned third-party-derived preliminary soil standards and is of the opinion that these standards meet the degree of scientific rigor required under the CSST procedures.

2.4 Derivation of Environmental Protection Standards – Livestock ingesting soil and fodder

Details related to the CSST, 1996 equations and parameter values used to derive a livestock ingesting soil and fodder protective preliminary soil standard for barium are presented in Appendix C.

A barium toxicity reference value (TRV) of 0.45 mg/kg/day in cattle, based on a maximum tolerable intake (CD) of 20 mg barium/kg diet (Puls, 1994) was calculated

and used in the derivation of the livestock ingesting soil and fodder preliminary matrix standard.
To protect livestock from ingesting barium contaminated soil and fodder at agricultural sites, a preliminary soil standard of 77 ug/g was calculated.

2.5 Derivation of Environmental Protection Standards – Major microbial functional impairment

Under the CSST, 1996 protocol, an agricultural land use matrix soil standard to protect major microbial function is not derived *de novo*. Rather, CSST recommended that when available for a particular substance, the CCME environmental health, nutrient and energy cycling check value be adopted as an appropriate major microbial functional impairment matrix soil standard.

Protocol details related to the derivation procedures used by CCME to calculate the environmental health, nutrient and energy cycling check value may be found in CCME, 1996; 2006.

For barium, CCME considers "data to be insufficient/inadequate to calculate an environmental health, nutrient and energy cycling check", (CCME, 1999).

Consequently, as no CCME nutrient and energy cycling check value is available, no standard (NS) is provided to protect major microbial function for agricultural land use in the proposed 2007 draft matrix soil standards for barium.

2.6 Derivation of Environmental Protection Standards – Groundwater flow to surface water used by aquatic life

Preliminary soil standards to protect freshwater and marine aquatic life from soluble barium leaching from contaminated soil into groundwater flowing to surface water used by aquatic life were derived in accordance with CSST, 1996 procedures. Under the CCST procedures, matrix soil standards to protect aquatic life from soil to water contaminant transfer are back-calculated using the ministry's approved groundwater transport model (B.C. Ministry of Environment, 2006) and the respective freshwater and marine CSR Schedule 6 aquatic life protective water quality standards. The CSR Schedule 6 freshwater and marine aquatic life standards for barium are:

10,000 ug/L - freshwater aquatic life, and
5,000 ug/L - marine and/or estuarine aquatic life, (British Columbia, 2005).

The following barium-specific parameter values were used in the groundwater transport model to back-calculate matrix soil standards to protect groundwater used by aquatic life:

Kd: 100 L/kg
t: 2,200 years.

The dissociation constant (Kd) value of 100 L/kg for barium is based on an empirical study, Estimation of a Generic Adsorption Coefficient Kd for Barium, (Lintott and Tindal, 2007). The study authors recommended adoption of a Kd value of 100 L/kg for barium to the Barite-Barium Issues Technical Advisory Committee. The ministry in turn has accepted the recommendation of the Barite-Barium Issues Technical Advisory Committee to use a Kd = 100 L/kg in deriving barium matrix soil standards to protect various water uses, including protection of aquatic life.

A value of 2,200 years was used for the "time since contamination release" parameter (t) in back calculating barium matrix soil standards to protect freshwater and marine aquatic life. This value of 2,200 years differs from the 100 years specified for parameter (t) in exhibit 7 of the CSST procedures (BC Environment, 1996). The value, t = 100 years listed in the CSST document is specific to organic substances. A value, t = 2,200 years is however, considered more appropriate for inorganic substances and has been consistently used by the ministry in back calculating matrix soil standards to protect various water uses for all other inorganic substances listed in Schedule 5 of the Contaminated Sites Regulation. Due to an editorial oversight, Exhibit 7 of the CSST, 1996 procedures only lists the value, t = 100 years, appropriate for use with organic substances.

Details of the other groundwater model parameter values used in the calculation of groundwater protective preliminary matrix soil standards for barium appear in Appendix D. [5]

To protect groundwater flowing to surface water used by aquatic life, the following preliminary matrix soil standards, applicable to all land uses, were calculated

Aquatic life	**Preliminary standard (ug/g)**
Freshwater	3,309
Marine	1,655

2.7 Derivation of Environmental Protection Standards – Groundwater used for livestock watering

Under the CCST, 1996 protocol, an agricultural land use matrix soil standard to protect groundwater used for livestock watering is back-calculated using the ministry's approved groundwater transport model (B.C. Ministry of Environment, 2006) and the CSR Schedule 6 livestock water quality standard for the particular substance.

[5] CSST, 1996 equations were used in calculating soil to groundwater protective standards

For barium, a Schedule 6 livestock water quality standard has not been authorized under the CSR (British Columbia, 2005). Therefore, no standard (NS) is provided to protect groundwater used for livestock watering in the ministry's proposed 2007 draft matrix soil standards for barium.

2.8 Derivation of Environmental Protection Standards – Groundwater used for irrigation

Under the CCST, 1996 procedures, a matrix soil standard to protect groundwater used for irrigation purposes at agricultural, urban park and residential sites is back-calculated using the ministry's approved groundwater transport model (B.C. Ministry of Environment, 2006) and the CSR Schedule 6 irrigation water quality standard for the particular substance.

For barium, a Schedule 6 irrigation water quality standard has not been authorized under the CSR (British Columbia, 2005). Therefore, no standard (NS) is provided to protect groundwater used for irrigation in the ministry's proposed 2007 draft matrix soil standards for barium.

2.9 CSST "Background" Adjustment

Using all regional data available for barium in the ministry's Soil Quality Database (B.C. Ministry of Environment, 2005) a provincial background soil quality estimate of 412 ug/g was calculated. The provincial background estimate represents the 95th percentile value calculated for provincial regions as a whole.

In accordance with the CSST, 1996 protocol, the provincial background soil quality estimate was compared to all preliminary matrix soil standards calculated for barium.

The preliminary standards calculated to protect drinking water (331 ug/g) and livestock ingesting soil and fodder (77 ug/g) were found to be less than the estimated provincial background concentration for barium.

Therefore, the preliminary matrix soil standards to protect drinking water and livestock ingesting soil and fodder were "capped" at a concentration equivalent to the provincial background concentration for barium (i.e. 412 ug/g).

2.10 Application of CSST Rounding-off Rule

As a final step, all calculated and background adjusted preliminary matrix soil standards were rounded in accordance with the CSST, 1996 "Rounding-off Rule" to derive the proposed 2007 draft matrix soil quality standards for barium.

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4. Exhibits

Exhibit 1. Proposed 2007 Draft Matrix Soil Standards for Barium

Exhibit 1. Proposed 2007 Draft Matrix Soil Standards for Barium

SCHEDULE 5

MATRIX NUMERICAL SOIL STANDARDS[1]
BARIUM (CAS# 7440-39-3)

COLUMN I	COLUMN II	COLUMN III	COLUMN IV	COLUMN V	COLUMN VI	Note
	SOIL STANDARD FOR PROTECTION OF SITE-SPECIFIC FACTOR					
Site-specific Factor	Agricultural (AL)	Urban Park (PL)	Residential (RL)	Commercial (CL)	Industrial (IL)	2
HUMAN HEALTH PROTECTION						
Intake of contaminated soil	6 500	6 500	6 500	20 000		3
Groundwater used for drinking water	400	400	400	400	400	4,5
ENVIRONMENTAL PROTECTION						
Toxicity to soil invertebrates and plants	1 000	1 000	1 000	1 500	1 500	
Livestock ingesting soil and fodder	400					5
Major microbial functional impairment	NS					6
Groundwater flow to surface water used by aquatic life						
Freshwater	3 500	3 500	3 500	3 500	3 500	4
Marine	1 500	1 500	1 500	1 500	1 500	4
Groundwater used for livestock watering	NS					7
Groundwater used for irrigation	NS	NS	NS			7

Notes

1. All values in ug/g unless otherwise stated. Substances must be analyzed using methods specified in a director's protocol or alternate methods acceptable to the director.
2. The site-specific factors of human intake of contaminated soil and toxicity to soil invertebrates and plants specified in this matrix apply at all sites.
3. Intake pathway of exposure modeled is inadvertent ingestion of soil.
4. Assumes barium Kd = 100 L/kg
5. Standard has been adjusted based on a reference provincial background soil concentration. Standard represents the reference provincial background soil concentration. For all land uses, the reference provincial background soil concentration is 412 ug/g.
6. NS – no standard. Insufficient acceptable scientific data exists, so no standard is calculated.
7. NS – no standard. No appropriate standard, guideline of criterion exists to use to develop a soil quality standard.

5. Tables

Table 1. Comparative Solubility and LD50 Values for Selected Barium Compounds

Barium Compound	Solubility (g/L)	Reference	LD50[1] (mg/kg)	Reference
Inorganic				
Barium chloride	375 @ 26°C	WHO, 2005a; Patty, 1981	118	US EPA, 1997
Barium nitrate	87 @ 20°C	WHO, 1999; Patty, 1981	355	US EPA, 1997
Barium hydroxide	56 @ 15°C	Patty, 1981	308	RTECS 2007
Barium fluoride	1.2 @ 25°C	Patty, 1981	250	US EPA, 1997
Barium chromate	0.0034 @ 16°C	WHO, 1990	3000	Dugan, 2007
Barium sulphate	0.00246 @ 25°C	Patty, 1981	> 160,000[2]	Boyd & Able, 1966
Organic				
Barium acetate	58.8 @ 20°C	WHO, 2005b	921	US EPA, 1997
Barium carbonate	0.02 @ 20°C	Patty, 1981	630	ORNL, 2007
Barium stearate	0.0035 @ 20°C	Chemtura, 2005	2506	RTECS, 2007

[1] LD_{50} values cited are acute oral values for adult rat.

[2] Dose approximates LD_0 for intra-gastric administration,
LD_{50} = 307 g/kg for gastric fissure via intra-gastric administration,
LD_{50} = 365 g/kg for intestinal occlusion via intra-gastric administration.

6. Appendices

Appendix A.	Members of the Barite-Barium Issues Technical Advisory Committee
Appendix B1.	Details of Derivation: Human Health Protection – Intake of contaminated soil, 2007 Draft Matrix Standards for Barium
Appendix B2.	Exposure Terms for Various Classes of Toxic Substances and Land Uses
Appendix C1.	Details of Derivation: Environmental Protection – Livestock ingesting soil and fodder, 2007 Draft Matrix Standards for Barium
Appendix C2.	Calculation of Barium TRV for Cattle
Appendix D.	Groundwater Model Parameter Values Used to Calculate Barium Preliminary 2007 Matrix Soil Standards to Protect Groundwater

Appendix A. Members of the Barite-Barium Issues Technical Advisory Committee

Chris Meloche (Committee Chair)
Husky Energy Inc. (CAPP)

Glyn Fox
BC Ministry of Environment

Peggy Evans
BC Ministry of Environment

Andrew Morgan
BC Ministry of Energy, Mines and Petroleum Resources

Oluwole Eweje
BC Ministry of Forests and Range

Thom Sedun
BC Oil & Gas Commission

Kyle Hegel
Talisman Energy (CAPP)

Mark Hugdahl (BCLQAAC Chair)
ALS Environmental

Miles Tindal
Axiom Environmental Inc.

Darlene Lintott
Bodycote Norwest Labs

Appendix B1. Details of Derivation: Human Health Protection – Intake of contaminated soil, 2007 Draft Matrix Standards for Barium

Adapted from Exhibit 9B, CSST Procedures, (BC Environment, 1996)

Barium – Simplified Human Health TDI-based "Intake of contaminated soil" Standard ($PSQS_{HH}$) – Threshold Substances

Note: $PSQS_{HH}$ equals Human Health Protective – Intake of contaminated soil, preliminary 2007 draft matrix standards for barium

Equation

$$PSQS_{HH} = \frac{[SAF \times TDI] \times BW}{(AF_I \times IR) \times ET}$$

Parameter	Definition (units)	Default
$PSQS_{HH}$	Preliminary Soil Quality Standard $_{Human\ Health}$ - TDI-based - (mg/kg)	Calculated value (Land Use specific)
SAF	Soil Allocation Factor	0.2
TDI	Tolerable Daily Intake (mg/kg BW/day)	0.2 [1]
BW	Body Weight (kg) child adult	 13 70
AF_I	Absorption Factor $_{ingestion}$ (unitless)	1.0
IR	Ingestion Rate soil (mg/day) child adult	 80 20
ET	Exposure Term (unitless)	Land use specific [2]

[1] US EPA, 2005b

[2] See Appendix B2

Appendix B2. Exposure Terms for Various Classes of Toxic Substances and Land Uses

Class of Toxic Substance	Receptor	Land Use	Exposure Term (ET)
Threshold	Child	Agricultural, Residential, Urban Parkland	1.00 [1]
Threshold	Child	Commercial	0.33 [2]

[1] ET = (24hr/24hr x 7d/7d x 52wk/52wk x 70yr/70yr)

[2] ET = (12hr/24hr x 5d/7d x 48wk/52wk x 70yr/70yr)

Appendix C1. Details of Derivation: Environmental Health Protection – Livestock ingesting soil and fodder, 2007 Draft Matrix Standards for Barium

Adapted from Exhibit 1, CSST Procedures (BC Environment, 1996)

Barium – Environmental Protection - Livestock ingesting soil and fodder standard

Note: C_S equals Environmental Protection – Toxicity to soil invertebrate and plants, preliminary 2007 draft matrix standards for barium

Equation

$$C_S = \frac{TRV \times BW}{[\,(Bv \times IR_{f)} + IR_S\,] \times AB \times ED \times AUF}$$

Parameter	Definition (units)	Default
C_S	Livestock ingesting soil and fodder standard	Calculated value
TRV	Toxicity Reference Value	chemical specific [1]
BW	receptor Body Weight (kg)	600 [2]
BV	Soil to plant transfer coefficient for vegetative tissue	0.15 [3]
IR_f	Ingestion Rate $_{fodder}$ (kg/d) or $0.687 \times BW^{0.651}$	13.5 [2]
IR_S	Ingestion Rate $_{soil}$ (kg/d) or $0.083 \times DMIR$	1.5 [2]
AB	Amount Bioavailable	1.0 (i.e. 100%)
ED	Exposure Duration	1.0 [4] (i.e. 365d/yr)
AUF	Area Use Function: Ratio of affected area / Range	1.0 [5] (i.e. 100%)
DMIR	Dry Matter Intake Rate (kg/d)	15 [2]

[1] See Appendix C2

[2] Default value for cattle

[3] Point estimate from Oak Ridge National Laboratory, ORNL, 1984

[4] ED is climate specific because the duration of exposure to the contaminant is dependent to a variable extent on the climate of the given region

[5] AUF is area specific since the receptors may not occupy the entire given area and the contaminant might not be uniformly distributed throughout the given area

Appendix C2. Calculation of Barium TRV for Cattle

Barium – Calculation of TRV for Cattle

Equation

$$TRV = \frac{CD \times IR_f}{BW}$$

Parameter	Definition (units)	Default
TRV	Toxicity Reference Value	Calculated value
CD	Upper bound of the high dietary concentration (mg/kg)	20 [1]
IR_f	Ingestion Rate $_{fodder}$ (kg/d)	13.5 [2]
BW	Body Weight (kg)	600 [2]

[1] Puls, 1994.

[2] Default value for cattle

Appendix D. Groundwater Model Parameter Values Used to Calculate Barium Preliminary 2007 Matrix Soil Standards to Protect Groundwater

Model Component	Parameter	Definition	Value	Units	Notes
Source Properties	X	Source length	5	m	
	Y	Source width	30	m	
	Xr	Distance to receptor	10	m	
	T	Time since contaminant release	2200	yr	
Aquifer Properties	N	Total porosity (saturated zone)	0.3		
	n_e	Effective porosity (saturated zone)	0.2		
	n_a	Air porosity (unsaturated zone)	0.2		
	n_w	Water porosity (unsaturated zone)	0.1		
	f_{oc}	Fraction organic carbon	0.006	dimensionless	
	P_b	Density	1.75	g/cm^3	
	K	Hydraulic conductivity	0.0001	m/s	
	I	Hydraulic gradient	0.004	m/m	
	d_a	Aquifer thickness	5	m/yr	
	I	Infiltration rate	0.55	m/yr	
Contaminant Properties	Kd	Barium:soil dissociation coefficient	100	mL/g	chemical specific
	H'	Henry's constant	0	dimensionless	
	$t_{1/2}$	Biodegradation half-life	0	Days	
	Solubility	Pure-phase solubility	11	mg/L	chemical specific
Water Quality Standards	$C_{schedule\ 6\ DW}$	CSR Schedule 6 Drinking water standard	1	mg/L	
	$C_{schedule\ 6\ AW}$	CSR Schedule 6 Aquatic Life standard	10	mg/L	Freshwater Aquatic Life
	$C_{schedule\ 6\ AW}$	CSR Schedule 6 Aquatic Life standard	5	mg/L	Marine Aquatic Life