Canadian Council of Ministers of the Environment
Le Conseil canadien des ministres de l'environnement

A PROTOCOL FOR THE DERIVATION OF GROUNDWATER QUALITY GUIDELINES FOR USE AT CONTAMINATED SITES

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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.

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READER COMMENTS

This protocol was published as a working document so that the revised methodology can be applied and tested. CCME recognizes that some refinements or changes may become necessary or desirable as scientific understanding of issues related to contaminated sites improves.

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NOTICE

This document provides the rationale and guidance for developing environmental and human health groundwater quality guidelines for contaminated sites in Canada. It is based on, and acts as a companion document to, A Protocol for the Derivation of Environmental and Human Health Soil Quality Guidelines (CCME, 2006). This document is intended for general guidance only, and does not establish or affect legal rights or obligations. It does not establish a binding norm, or prohibit alternatives not included in the document and is not finally determinative of the issues addressed. Decisions in any particular case will be made by applying the law and regulations on the basis of specific facts when regulations are promulgated or permits are issued.

OVERVIEW

The Canadian Council of Ministers of the Environment (CCME) has established a framework for assessing and remediating contaminated sites in Canada and developing scientific tools to promote consistency and provide guidance. This document establishes a framework for the development of Canadian Groundwater Quality Guidelines that can be added to the existing suite of Canadian Environmental Quality Guidelines. These groundwater quality guidelines will be used at contaminated sites in conjunction with Canadian soil quality guidelines and Canadian soil vapour guidelines.

This protocol considers the effects of contaminated groundwater exposure on human and ecological receptors. The pathways and receptors considered in the derivation of groundwater quality guidelines were selected based on exposure scenarios contained in A Protocol for the Derivation of Environmental and Human Health Soil Quality Guidelines (CCME, 2006). The groundwater protocol represents a separate and abbreviated version of CCME (2006) where key policy and technical elements needed to derive groundwater-specific guidelines were extracted. In contrast to soil quality guidelines, groundwater quality guidelines are independent of land use except for indirect exposure of humans via the infiltration of volatile contaminants into indoor air from groundwater, where separate guidelines are derived for both an agricultural/residential and a commercial/industrial scenario for this pathway.

Procedures for deriving groundwater quality guidelines were developed to either maintain specific uses of groundwater (e.g., irrigation or drinking water), or protect receptors in environments that may directly or indirectly come into contact with contaminated groundwater due to contaminant migration (e.g., surface waterbodies or vapour intrusion into basements). The groundwater quality guidelines are not intended to protect organisms living in aquifers, but rather to protect the uses of groundwater or downgradient receptors.

Groundwater quality guidelines are primarily derived using existing benchmarks (e.g., Canadian Water Quality Guideline) and back-calculating a groundwater concentration, using fate and transport models, that will not result in an exceedence of the benchmark once the contaminant reaches the environment of concern (e.g., surface waterbody). In cases where exposure to groundwater is through untreated well water, the benchmark (e.g., Guidelines for Canadian Drinking Water Quality) is adopted directly as the groundwater quality guideline.

This protocol addresses groundwater exposure through:

- saturated zone transport to surface water
- rising water table into shallow soils
- migration of vapours into indoor air
- use of well water.

The final generic groundwater quality guideline is based on the lowest value generated by the environmental and human health approaches. Generic guidelines can be altered to account for site-specific conditions. For more information on setting site-specific objectives, see section 1.1 of CCME (2006), suggestions presented in this document, and Guidance Manual for Developing Site-Specific Soil Quality Remediation Objectives for Contaminated Sites in Canada (CCME 1996a).

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ACKNOWLEDGEMENTS

This groundwater protocol is primarily based on A Protocol for the Derivation of Environmental and Human Health Soil Quality Guidelines (2006). David Williams and Ian Mitchell of Meridian Environmental Inc. and Miles Tindal of Axiom Environmental Inc. were primarily responsible for adapting the soil protocol to produce groundwater values, and for devising new methods in guideline development specifically for groundwater. Valuable input was provided by members of the CCME Soil Quality Guidelines Task Group, and through public review comments.

DOCUMENT ORGANIZATION

This document is divided into four parts, consistent with A Protocol for the Derivation of Environmental and Human Health Soil Quality Guidelines (CCME, 2006). A glossary of terms is presented at the beginning of the document. Background information on the development of the Protocol, including the scientific tools that have been developed to help assess and remediate contaminated sites in Canada is provided in Part A. Information on the principles of the groundwater quality guidelines derivation protocol is also included in Part A. The processes for deriving environmental and human health guidelines are described in Part B and Part C, respectively. Part D concludes this document by providing guidance on selection of the final groundwater quality guideline. Equations and model input parameters are provided in the appendices.

LIST OF FREQUENTLY USED ACRONYMS AND ABBREVIATIONS

CCME	Canadian Council of Ministers of the Environment
EDI	Estimated daily intake
GWQG	Groundwater quality guideline
$GWQG_{GC}$	Groundwater quality guidelines for groundwater contact by soil-dependent organisms
$GWQG_{FL}$	Groundwater quality guidelines for the protection of freshwater life
$GWQG_{ML}$	Groundwater quality guidelines for the protection of marine life
$GWQG_{LW}$	Groundwater quality guidelines for the protection of livestock watering
$GWQG_{IR}$	Groundwater quality guidelines for the protection of irrigation water
$GWQG_{PW}$	Groundwater quality guidelines for the protection of potable water
$GWQG_{IAQ\text{-}R}$	Groundwater quality guidelines for the protection of indoor air quality – residential
$GWQG_{IAQ\text{-}C}$	Groundwater quality guidelines for the protection of indoor air quality – commercial
$GWQG_{M}$	Groundwater quality guidelines for management considerations
$GWQG_{F}$	Final groundwater quality guidelines
LOEC	Lowest Observed Effect Concentration
NA	Not applicable
NAPL	Non-aqueous phase liquid
PHC CWS	Canada-wide Standard for Petroleum Hydrocarbons in Soil
RSC	Risk-specific concentration
RSD	Risk-specific dose
RTDI	Residual tolerable daily intake
SQG_{SC}	Soil Quality Guidelines for soil contact by soil-dependent organisms
SQGTG	Soil Quality Guidelines Task Group
TC	Tolerable concentration
TDI	Tolerable daily intake
TRV	Toxicity reference value
US EPA	United States Environmental Protection Agency

GLOSSARY

This section contains only some of the terms that are specific for this groundwater protocol. For more comprehensive glossaries please refer to A Protocol for the Derivation of Environmental and Human Health Soil Quality Guidelines (CCME, 2006) and Canadian Environmental Quality Guidelines (1999).

Aquifer: Groundwater-bearing formations sufficiently permeable to transmit and yield water in usable quantities.

Attenuation factor: A value applied within the calculation of the Indoor Air Quality guidelines to address the decrease in concentration as contaminants are transported from soil vapour to the receptor.

Background (ambient and natural)

Ambient concentration: A representative ambient level for a contaminant in soil or water. Ambient concentrations may reflect natural geological variations in relatively undeveloped areas or the influence of generalized industrial or urban activity in a region.

Natural background: Representative, naturally occurring level of a substance in the environment. Reflects natural geologic variations.

Background exposure: Exposure to receptors from ambient concentrations of contaminants.

Biodegradation: A microbiologically mediated process (e.g., due to the action of bacteria, yeasts, and fungi) that chemically alters the structure of a chemical, the common result being the breakup of the chemical into smaller components.

Biota: Biological organisms including plants, microbes, invertebrates, and animals.

Capillary fringe or capillary zone: The zone directly above the water table into which groundwater is drawn by capillary action.

Carcinogen: A substance or agent that causes the development or increases the incidence of cancer. A carcinogen can also act upon a population to change its total frequency of cancer in terms of numbers of tumours or distribution by site and age.

Coarse-grained soil: Soil which contains greater than 50% by mass particles greater than 75 µm mean diameter (D_{50} > 75 µm).

Contaminant retardation: Impairment of contaminant movement through the subsurface by physical or chemical means.

Contaminant: Any substance present in an environmental medium (e.g., water, air, soil) at concentrations in excess of natural background or that does not naturally occur in the environment.

Darcy velocity: A term used to describe groundwater flow through a porous medium, equal to the product of the saturated hydraulic conductivity and the hydraulic gradient (as opposed to the groundwater velocity, which is the average linear pore water speed). Synonyms for Darcy velocity include Darcy flux, volumetric flux density, and specific discharge.

Degradation: The chemical, physical, and biological breakdown of contaminants.

Dilution factor: A constant applied to groundwater quality guidelines to address the decrease in concentration as contaminants are transported to surface water due to dilution.

Domenico model: Mathematical model used to predict changes in contaminant concentration in groundwater due to advection, dispersion and biodegradation during transport.

Domestic water: Water used by humans for household purposes, such as drinking, bathing, washing clothes, food preparation, and watering lawns and gardens.

Ecological receptor: A non-human organism potentially experiencing adverse effects from exposure to contaminated media either directly (contact) or indirectly (food chain transfer).

Ecosystem: A dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit.

Exposure pathway: The means by which organisms are exposed to contaminants. The main categories of exposure pathways for humans or ecological receptors include (i) direct transfer from the surrounding medium of contaminants (from air, water, soil or sediment) by dermal uptake or absorption across external epithelial solution, (ii) ingestion of contaminated water, and (iii) inhalation of contaminated vapours. The exposure pathway may also refer more generally to the media from which an organism is exposed (air, water, soil, sediment, or combination thereof) and route of contaminant transport from source to receptor.

Fine-grained soil: Soil which contains greater than 50% by mass particles equal to or less than 75 μm mean diameter ($D_{50} \leq 75$ μm).

Groundwater: Subsurface water beneath the water table in fully saturated geologic formations.

Hypolentic zone: Transition zone between groundwater and surface water beneath lakes and wetlands.

Hyporheic zone: Transition zone between groundwater and surface water beneath streams and rivers.

Multi-tier framework: A guideline system using multiple approaches (tiers) to setting remediation objectives. The same level of protection is applied regardless of the tier selected, but allows for more realistic remediation targets to be established by collecting additional data from individual sites.

Non-threshold contaminant: A contaminant for which it is assumed that there is risk associated with any amount of exposure (i.e., it is assumed that there is no threshold for effects).

Offset distances: A minimum distance from a receptor where guidelines do not apply, due to limitations in transport models or other invalidated guideline assumptions.

Pathway: see ‘exposure pathway’.

Partitioning relationship: Equation used to represent the relationship between chemical concentration of the contaminant in soil, and porewater and soil vapour at equilibrium.

Receptor: A receptor is the person or organism exposed to a chemical. For human health risk assessment, it is common to define a critical receptor as the person expected to experience the most severe exposure (due to age, sex, diet, lifestyle, etc.) or most severe effects (due to state of health, genetic disposition, sex, age, etc.) as a result of that exposure.

Recharge: Process which occurs when the water content of the unsaturated zone becomes high enough to cause excess water to percolate downward to the water table, usually as a result of the infiltration of snow melt or rainwater into surface soils. Using a water balance approach, recharge is equal to the total amount of precipitation less the amount of surface runoff and evapotranspiration.

Remediation: The management of a contaminated site to prevent, minimize, or mitigate damage to human health or the environment. Remediation may include both direct physical actions (e.g., removal, destruction, and containment of contaminants) and institutional controls (e.g., zoning designations or orders).

Risk: In CCME protocols, risk is a measure of both the severity of health effects from exposure to a substance and the probability of its occurrence. Risk may involve quantitative extrapolation from animals to humans or from high dose/short exposure time to low dose/long exposure time. Risk may consider potency (physical/chemical properties, biological reactivity), susceptibility (metabolic activation, repair mechanisms, age, sex, hormonal factors, immunological status), level of exposure (sources, concentration, initiating events, routes, pathways), and adverse health effects (nature, severity, onset, reversibility).

Risk-based approach: A procedure used to determine the qualitative aspects of hazard identification, and usually a quantitative determination of the level of risk based on deterministic or probabilistic techniques.

Saturated soil: Soil in which the maximum possible amount of soil pore water is present. Considered to be below the water table.

Slope factor: The relationship between an exposure dose or concentration and the risk of developing cancer. Expressed as risk per weight of chemical per unit of body weight per day.

Soil pore water: The water occupying the space between particles of sediment or soil.

Solubility: The maximum concentration of a chemical that can be dissolved in water when that water is both in contact and at equilibrium with the pure chemical.

Subsurface: Unconsolidated regolith material above the water table not subject to soil forming processes.

Stygobitic: Organisms which live in groundwater.

Threshold contaminant: A contamination for which there is a dose/concentration below which no adverse effects are expected to occur.

Tolerable concentration: An estimate (with *uncertainty* spanning perhaps an order of magnitude) of continuous inhalation exposure to the human population, including sensitive subgroups, that is likely to be without appreciable risk of deleterious effects during a lifetime. It is used to evaluate potentially non-carcinogenic effects only.

Tolerable daily intake: The level/rate of chemical exposure to which a person may be exposed with no expected adverse effects. A tolerable daily intake can only be determined for chemicals with threshold effects (i.e., non-carcinogens).

Transition zone: The area where groundwater enters a surface water body (see **Hypolentic** or **Hyporheic**). Also referred to as the discharge zone.

Unconfined aquifer: A region of saturated ground material not overlain by a low-permeability layer such as clay, whose upper water surface (water table) is at atmospheric pressure, and thus is able to rise and fall. These systems allow for the draining of soil pore water and the subsequent movement of air (or water) to fill the spaces vacated by the moving water.

Unit risk: see 'slope factor' for definition, except expressed as risk per unit of concentration.

Unsaturated soil: Soil in which there is less than the maximum possible amount of soil pore water present (considered to be above the water table).

Vadose zone: The zone containing water under pressure less than that of the atmosphere, including soil water, intermediate vadose water, and capillary water. This zone is limited above by the land surface and below by the surface of the zone of saturation, that is, the water table.

Volatilization: The chemical process by which chemicals spontaneously convert from a liquid or solid state into a gas and then disperse into the air above contaminated soil.

Water table: Depth below which soil is saturated with groundwater

PART A

1. Background and Context

The Canadian Council of Ministers of the Environment (CCME) has developed and published environmental quality guidelines for several different media, compiled in the Canadian Environmental Quality Guidelines (CCME, 1999). These guidelines are routinely used for the assessment and remediation of federal contaminated sites, and also have been adopted by several other Canadian jurisdictions. The CCME Soil Quality Guidelines Task Group (SQGTG) is responsible for the development of soil quality guidelines, based on A Protocol for the Derivation of Environmental and Human Health Soil Quality Guidelines (CCME, 2006), and referred to herein as the “soil protocol”.

Groundwater is used as the primary source of drinking water by approximately 10% of Canadians (Statistics Canada, 2011). It is also the primary source of water used for livestock watering and crop irrigation, and is used by the manufacturing, mining and petroleum industries (Environment Canada, 1999; Government of Canada, 2003). In recent years, groundwater has also been used to heat and cool buildings (Environment Canada, 1999).

There is also significant ecological use of groundwater. Groundwater can interact with surface water, and therefore is often a source of the water on which aquatic life depends. Shallow groundwater is also closely linked with soil, and organisms in soil may therefore be exposed to contaminants present in groundwater due to periodic inundation with groundwater or capillary rise.

Groundwater contamination is common at many contaminated sites, particularly those with relatively soluble contaminants and soil contamination extending to or near the water table. In many cases groundwater contamination may be associated with soil contamination; however, groundwater plumes may extend beyond the area affected by soil contamination, or, in the case of highly soluble contaminants, the contamination may be present primarily in the dissolved phase.

Canadian Soil Quality Guidelines (CCME, 1999) include consideration of the protection of groundwater for organic chemicals as an intermediate step in the calculation of soil quality guidelines for the protection of aquatic life. However, groundwater quality guidelines were not included in the publication of Canadian soil quality guidelines. In the absence of groundwater quality guidelines, potable water guidelines and/or surface water quality guidelines, particularly the Guidelines for Canadian Drinking Water Quality (Health Canada, 2010a), and the Canadian Water Quality Guidelines for the Protection of Aquatic Life (CCME, 1999), are often applied for groundwater – either directly or with an arbitrary adjustment factor. While the protection of potable water and aquatic life would need to be considered in any groundwater quality guidelines, in some cases there is no potable water use and no nearby surface water, or a large separation between the source of groundwater contamination and any nearby surface water may result in the application of surface water guidelines to groundwater as overly conservative. Furthermore, there are additional exposure pathways relevant for groundwater which are not explicitly considered in the above guidelines, including volatilization of contaminants from groundwater into enclosed indoor spaces of homes and subsequent inhalation, and direct contact of plants and soil invertebrates with groundwater. Therefore, there is a need for consistent, comprehensive and defensible groundwater quality guidelines.

This document establishes a framework for the development of Canadian Groundwater Quality Guidelines (GWQG) that ensures an appropriate level of protection for both human and environmental receptors. This document serves as a companion document to the soil protocol. The pathways and receptors used to derive groundwater quality guidelines are based on those in the soil protocol and, except as discussed in Section A.4 below, the models and assumptions used are the same. The soil protocol should be consulted for additional background and underlying principles; detailed information from the soil protocol was not duplicated in this document.

At present, this protocol only applies to organic substances, due to the high level of uncertainty and variability in the fate and transport of inorganic substances in groundwater, including highly variable soil-water partitioning and contaminant transport rates highly dependent on soil chemistry, as well as the absence of biodegradation resulting in negligible reduction in concentrations during transport when using the methods developed for organic substances.

For certain water uses (e.g., drinking water, agricultural water uses), existing Canadian Water Quality Guidelines for those uses are adopted directly into the Canadian groundwater quality guidelines. Where contaminant transport from the source is required before exposure occurs (e.g., protection of indoor air quality, aquatic life, plants and invertebrates), fate and transport models are used to derive the guidelines.

2. Framework for the Derivation of Groundwater Quality Guidelines

2.1 What is the Protocol?

This protocol was developed to guide the establishment of scientifically defensible generic guidelines for organic chemicals in groundwater at contaminated sites across Canada, in parallel with soil quality guidelines derived using the soil protocol (CCME, 2006). The protocol details the steps needed to generate effects-based groundwater remediation guidelines. Some information on the rationale for the choice of receptors, exposure pathways, models, assumptions and minimum data requirements is provided, with reference to further supporting rationale in the soil protocol.

The guidelines are developed and/or revised on a substance-by-substance basis as required, in accordance with the protocol, after a comprehensive review of the physical/chemical characteristics, background levels in Canadian groundwater and other media, toxicity and environmental fate and behaviour of each substance. This supporting information is presented in a series of guideline-supporting technical documents from CCME, or from CCME member jurisdictions.

2.2 Guiding Principles

The development of generic guidelines is based on both scientific and management/policy considerations, and takes into consideration risks to both the environment and human health. In many respects the guiding principles for the development of groundwater quality guidelines are similar to those for the development of soil guidelines, described in Section A.2.2 of the soil protocol.

The groundwater protocol is not oriented towards the protection of receptors residing in groundwater (e.g., stygobitic organisms), but rather receptors in other media which may be exposed to groundwater contamination. Ecological receptors protected include aquatic life in nearby surface water (freshwater or marine), livestock (via dugouts and livestock wells), crops (irrigation water), as well as plants and invertebrates in soil in contact with groundwater (i.e., phreatophytes) or periodically inundated with groundwater (used as a surrogate for the overall ecological function of soil). Human exposure considers both direct exposure (ingestion of groundwater) and indirect exposure (volatilization and migration of contaminants into indoor air; inhalation of volatiles while bathing, dermal contact while bathing).

The level of protection afforded by the groundwater quality guidelines for ecological receptors has generally been previously established through the derivation of existing guidelines (Canadian Water Quality Guidelines for the Protection of Aquatic Life, Canadian Water Quality Guidelines for the Protection of Agricultural Water Uses; Irrigation Water and Livestock Watering, and Soil Quality Guidelines for Soil Contact – i.e., the protection of plants and soil invertebrates; CCME, 1999) which are employed in the derivation of environmental groundwater quality guidelines. Human health groundwater quality guidelines are concentrations in groundwater at or below which no appreciable human health risk is expected from long-term exposure; for the ingestion of water (or exposure while showering or bathing), the existing Guidelines for Canadian Drinking Water Quality (Health Canada, 2010a and updates) are adopted directly.

2.3 Water Uses

As discussed in Section A.1 above, groundwater is used for several different purposes in Canada; these uses form the basis for most of the exposure pathways (i.e., routes of exposure from source to receptor) evaluated during guideline derivation. The specific uses include use of groundwater by humans as a drinking or domestic water source and use of groundwater for livestock watering or crop irrigation. Groundwater may also interact with surface water, which is used as a habitat for aquatic life or as a source of water for both human and ecological receptors.

2.4 Land Use

Soil quality guidelines are derived for four defined land uses (agricultural, residential/parkland, commercial and industrial), as described in Section A.2.3 of the soil protocol. Land use is generally less important for groundwater quality guidelines, however, since most groundwater uses are independent of land use.

The exception is the indirect exposure of humans via the infiltration of volatile contaminants into indoor air from groundwater. Guidelines are established for both an agricultural/residential and a commercial/industrial scenario for this pathway. Some jurisdictions may allow for the exclusion of the agricultural/residential guideline at commercial or industrial sites, although there may be requirements for offset distances from more sensitive land uses to reflect the mobility of both groundwater and soil vapours.

2.5 Chemicals Classification

Section A.2.4 of the soil protocol (CCME, 2006) classifies chemicals as organic or inorganic, dissociating or non-dissociating, volatile or non-volatile, and soluble or non-soluble. These same classifications are used for this protocol.

As noted earlier, this protocol has been developed for organic chemicals only. It is expected that groundwater quality guidelines would be necessary only for chemicals classified as soluble (i.e., chemicals which may be present in water at a concentration high enough to pose a human health or environmental risk). Groundwater guidelines for microorganisms and aesthetic concerns (e.g., taste and colour) are best addressed using Guidelines for Canadian Drinking Water Quality. Only chemicals which are considered volatile or semi-volatile require guidelines based on the indoor vapour inhalation pathway (see Appendix D of A Protocol for the Derivation of Soil Vapour Quality Guidelines for Protection of Human Exposures via Inhalation of Vapours (CCME, 2014) for determination of volatile compounds).

2.6 Soil Type

Contaminant fate and transport, including the movement of dissolved contaminants in groundwater and the migration of vapours towards buildings, is dependent to some extent on soil properties, many of which are related to soil texture. To minimize the uncertainty in guideline derivation introduced by soil variability, the protocol considers two generic soil types: coarse-textured soils (soils containing predominantly sand sizes) and fine-textured soils (soils containing predominantly silt and clay sizes). The criterion distinguishing the two categories is a median grain size of 75 microns. Generic soil properties representative of typical soils in each category have been assigned for the purposes of guideline development; these are summarized in Appendix B.

It should be noted that an individual jurisdiction may choose to take soil type into account only on a site-specific basis.

2.7 Summary of the Guideline Development Process

The guideline development process is detailed in Parts B through D of this document. A brief summary of the process is presented below.

Separate guidelines are developed for several defined environmental and human exposure pathways. The environmental pathways include plants and soil invertebrates exposed to groundwater, migration to surface water bodies inhabited by freshwater or marine life, and use of groundwater for livestock watering or crop irrigation. Human health pathways include the ingestion of drinking water and dermal and inhalation exposure during showering, based on the Guidelines for Canadian Drinking Water Quality (Health Canada, 2010a) where possible, and volatilization of groundwater contaminants and migration to indoor air. The receptors and exposure pathways considered are summarized in Figure 1.

The lowest of the guidelines established for each exposure pathway becomes the final groundwater quality guideline ($GWQG_F$). The $GWQG_F$ is also checked against non-toxicity considerations and typical background groundwater concentrations.

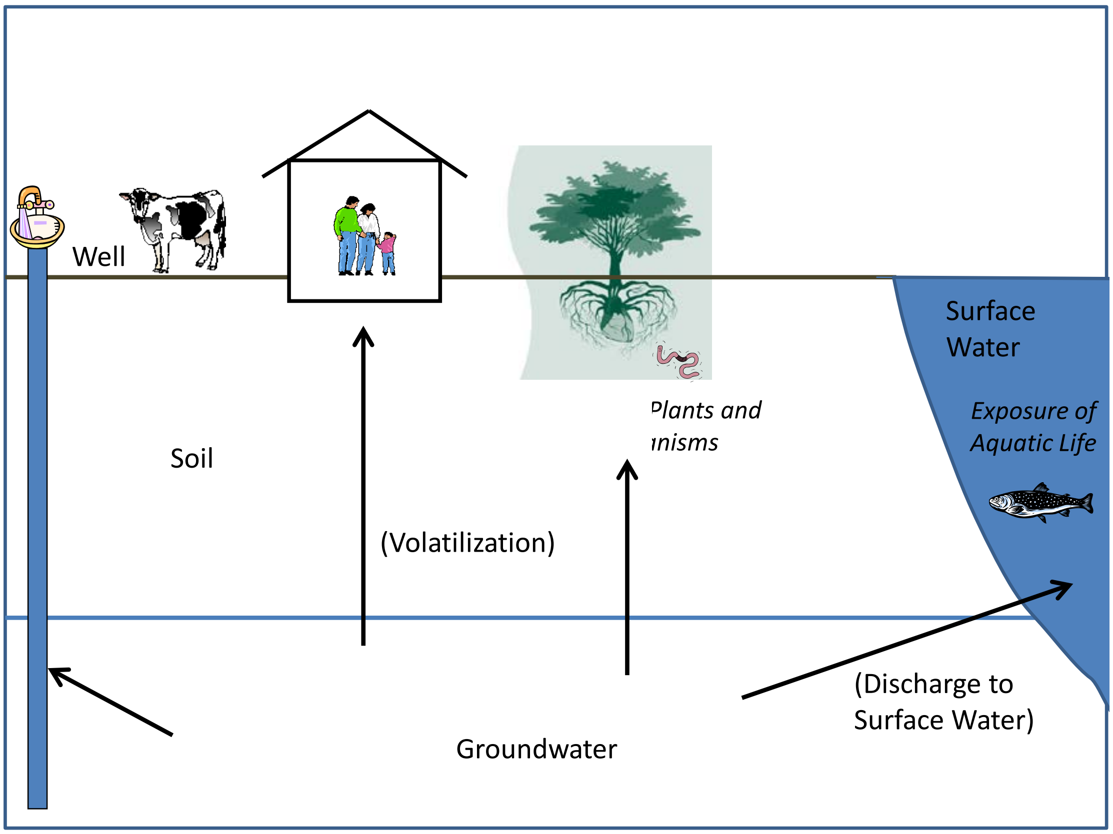

Figure 1: Receptors and Exposure Pathways Considered in Guideline Development

3. Use of Canadian Groundwater Quality Guidelines

3.1 General

Groundwater quality guidelines represent "clean down to levels" at contaminated sites and not "pollute up to levels" for less contaminated sites. They are not intended to be used to manage pristine sites. Remediating groundwater to groundwater quality guidelines is also not expected to return a contaminated site to pristine conditions (i.e., background). Groundwater quality guidelines may be used as an intermediate goal in returning a contaminated site to background groundwater quality, however, the decision of how far to “clean to” rests with individual jurisdictions.

The Canadian Groundwater Quality Guidelines are intended to be used for assessing in-place contaminants in groundwater. They are not intended for evaluating the quality of wastes or other substances being discharged to groundwater. The guidelines are also not intended for application at the point of exposure (e.g., water distribution systems or surface water). Use of the groundwater quality guidelines for anything other than their intended purpose should only be done with great care and an understanding of the guideline development process and its relevance to the proposed use. The groundwater quality guidelines must not be considered as permission to contaminate up to a certain level.

The generic guidelines are intended to be protective for any groundwater within an aquifer, regardless of the depth at which the groundwater is found or sampled, and regardless of how the groundwater is used. As discussed in Section 3.2 below, the guidelines are implemented within a tiered framework which may allow for site-specific consideration of the likelihood of exposure based on depth and potential uses.

The guidelines should be used in combination with acceptable sampling and analytical methods. Guidance documents on sampling methods, site characterization, and analytical guidance have been published by CCME (CCME, 1993a,b).

Several uncertainties apply to effects-based groundwater quality guidelines. Uncertainties related to soil guidelines, as discussed in Section A.3 of the soil protocol, are also generally applicable to groundwater quality guidelines.

3.2 Tiered Framework

Consistent with soil quality guidelines, groundwater quality guidelines are intended to be applied within a multi-tiered framework at contaminated sites. The tiers include:

- direct application of the generic numerical guidelines (Tier 1)
- limited modification of guidelines based on site-specific conditions (Tier 2)
- use of site-specific risk assessment to develop Site-Specific Remediation Objectives (Tier 3)

While this protocol is concerned primarily with the development of generic numerical guidelines, it is anticipated that it may also be used as the basis for the other tiers, particularly the modification of guidelines based on site-specific conditions (Tier 2). Specific requirements for the application of these tiers are left to the jurisdiction; some general guidance is provided below.

One method of modifying guidelines based on site-specific conditions is the elimination of guidelines for exposure pathways that are not operative at or near a contaminated site. Individual jurisdictions may specify requirements for the elimination of specific pathways. These requirements may in some cases be based on land use. For example, jurisdictions may allow the elimination of the exposure pathway to livestock and irrigation watering at land uses other than agricultural, or the elimination of the agricultural/residential land use vapour inhalation guideline at commercial or industrial sites; an offset distance from more sensitive land uses may be required in some jurisdictions. It may also be allowable to eliminate the guideline for the protection of potable water where there is no likelihood of contaminated groundwater being used as a source of drinking water or affecting drinking water supplies, or to eliminate surface water-related exposure pathways if there are no surface water bodies in the vicinity of the site. Further discussion of these pathways is provided in Parts B and C of this document; in all cases the requirements of the jurisdiction with authority over the site should be determined.

Site-specific guidelines may also be established by re-calculating guidelines using the models presented in Appendix A with site-specific values substituted for default model parameters. In general, only stable and readily measurable parameters should be adjusted, and only within ranges appropriate for the models. Further guidance on these adjustments, including suggested allowable ranges for model parameters, can be found in Appendices C and D of the Canada-wide Standard for Petroleum Hydrocarbons in Soil: User Guidance (CCME, 2008a), Guidance Manual for Developing Site-Specific Soil Quality Remediation Objectives for Contaminated sites in Canada (CCME 1996a), or guidance documents published by specific jurisdictions. Again, the requirements of the jurisdiction should be confirmed prior to modifying the guidelines.

Site-specific risk assessment, sometimes referred to as Tier 3, may involve the use of different models and assumptions, and generally requires more site-specific data than application of the generic guidelines or site-specific modification of guidelines. Detailed guidance on site-specific risk assessment is beyond the scope of this document; guidance has been published by agencies such as Environment Canada, Health Canada, CCME and several international agencies. Particularly relevant documents for federal contaminated sites include:

- A Framework for Ecological Risk Assessment: General Guidance (CCME, 1996b).
- A Framework for Ecological Risk Assessment: Technical Appendices (CCME, 1997).
- Federal Contaminated Sites Risk Assessment in Canada Part I: Guidance on Human Health Preliminary Quantitative Risk Assessment (PQRA), Version 2.0 (Health Canada, 2010b).
- Federal Contaminated Sites Risk Assessment in Canada Part II: Health Canada Toxicological Reference Values (TRVs) and Chemical-Specific Factors, Version 2.0 (Health Canada, 2010c).
- Federal Contaminated Sites Risk Assessment in Canada Part V: Guidance on Human Health Detailed Quantitative Risk Assessment for Chemicals ($DQRA_{CHEM}$) (Health Canada, 2010d).
- A Protocol for the Derivation of Environmental and Human Health Soil Quality Guidelines (CCME, 2006).
- Guidance on the Site-Specific Application of Water Quality Guidelines in Canada: Procedures for Deriving Numerical Water Quality Objectives (CCME, 2003).
- Guidelines for Canadian Drinking Water Quality, Summary Table and Technical Documents (Health Canada, 2010a)

3.3 Limitations on the Use of the Generic Numerical Guidelines

Groundwater quality guidelines are developed using a specific set of assumptions and models. In some cases, the assumptions used to derive these guidelines may not be protective for particularly sensitive sites. Any of the following conditions may invalidate the assumptions used to develop groundwater quality guidelines for specific exposure pathways:

Contaminated groundwater within 10m of a surface water body
For contaminated groundwater within 10 m (laterally and vertically) of a surface water body, accounting for potential seasonal fluctuations in water and the transition zone (i.e., measuring from the potential high water mark), the Canadian Water Quality Guidelines for the Protection of Aquatic Life should also be applied directly for the protection of aquatic life. If the surface water body is a potential drinking water source, the Guidelines for Canadian Drinking Water Quality may also apply.

Groundwater flow to stagnant water bodies
If contaminated groundwater is discharging into a stagnant water body (a water body without significant outflow), persistent contaminants may be concentrated through evaporation. A site-specific risk assessment for the protection of aquatic life is normally required in this scenario (i.e., aquatic life pathway in this protocol may not be sufficiently protective).

Fractured bedrock or fractured silt/clay
The transport models used to develop the generic guidelines assume that contaminant transport occurs through unconsolidated soils. If transport between the contaminant source and receptor (e.g., surface water body) is through fractures instead of unconsolidated soils, either a transport distance of zero should be assumed (i.e., the Canadian Water Quality Guidelines for the Protection of Aquatic Life should also be applied to groundwater), or a site-specific risk assessment should be conducted. This limitation also applies for the indoor vapour inhalation exposure pathway when a building slab is in direct contact with fractured bedrock. It is expected that the generic (Tier 1) guidelines would be protective for unfractured consolidated soils.

Very coarse textured soils enhancing transport or high groundwater velocity
Very coarse (e.g., gravel) soils at a specific site may result in enhanced contaminant transport at that site compared to what was assumed in the derivation of the generic guidelines. Since biodegradation is assumed in the groundwater transport model, a groundwater velocity higher than that assumed for the generic guidelines may result in significantly less biodegradation during transport, causing the guidelines to be non-conservative. Other scenarios resulting in a high groundwater velocity (e.g., tidal influences close to a marine water body) may also enhance contaminant transport. If the Darcy groundwater velocity exceeds $3x10^{-7}$ m/s, the groundwater transport modelling conducted for the generic guidelines may not be protective of nearby surface water bodies; in this case, a site-specific adjustment of the guidelines will likely be necessary. Very coarse soils may also affect the vapour inhalation exposure pathway if they are present directly beneath the building foundation at thicknesses greater than 30 cm.

Contaminated groundwater within 100 cm of a building foundation
The models used to evaluate vapour intrusion are not considered valid if the source of contamination is very close to the building; groundwater contaminated by organic contaminants

in direct contact with a building in particular is considered to be a high risk situation. In the event that contaminated groundwater (including capillary fringe) is present within 100 cm of a building foundation, the site must be addressed at Tier 2 or Tier 3.

Earthen Floors or Other Unusual Structural Features
The vapour intrusion model assumes a typical residential or commercial/industrial building with a concrete foundation slab. The presence of a building with an earthen floor within 10 m (laterally and vertically) of groundwater contamination indicates that a site-specific risk assessment is required. Other unusual building features (e.g., unusually low air exchange rate) may need to be addressed in a site-specific risk assessment or site-specific guideline modification for the vapour inhalation exposure pathway.

4. Deviations from *A Protocol for the Derivation of Environmental and Human Health Soil Quality Guidelines*

While in general this protocol is based on the soil protocol (CCME, 2006), there are some aspects where it deviates from the soil protocol, either due to unique considerations for groundwater or to reflect changes in science and policy since the soil protocol was published. Specific deviations include:

- Groundwater quality guidelines are not developed separately for the four land uses defined in the soil protocol. Separate vapour inhalation guidelines are calculated based on agricultural/residential and commercial/industrial exposure scenarios, however, jurisdictions may allow for the exclusion of certain exposure pathways based on land use, potentially subject to offset distances to more sensitive land uses.
- Groundwater quality guidelines for the protection of plants and soil organisms are calculated based on a single level of protection, equivalent to the Soil Quality Guideline for Soil Contact for the agricultural land use.
- Certain input parameters for the fate and transport models have been updated to reflect recent improvements in the science and research reflected in the 2008 update of the Canada-wide Standard for Petroleum Hydrocarbons in Soil (CCME, 2008b), or since.

PART B

1. Derivation of Environmental Groundwater Quality Guidelines

The overall purpose of environmental groundwater quality guidelines is to identify concentrations of contaminants in groundwater below which minimal or no adverse ecological effects are expected, depending on the receptors of interest, over the long-term. In order to set such concentrations, a wide range of decisions and assumptions are required, including, among others, which ecological effects, which exposure pathways, which receptors, and what level of protection to consider. There is significant discussion in Section B of the soil protocol (CCME, 2006) explaining how these decisions were made for soil quality guidelines. This groundwater protocol uses the soil protocol as a starting point, and adapts the scenarios in the soil protocol to be applicable to a contaminant source in groundwater. In this document, Section B 2 provides a high level discussion of appropriate protection goals for groundwater quality guidelines. Section B 3 examines the exposure scenario assumptions explicit and implicit in the groundwater quality guidelines. Section B 4 provides the detailed derivation process for environmental groundwater quality guidelines. Details of the models used are provided in Appendix A, and default model parameters are provided in Appendix B. As far as possible, material already present in the soil protocol is referred to rather than repeated.

2. Level of Ecological Protection and Relevant Endpoints

2.1 Level of Ecological Protection

Before groundwater quality guidelines can be derived, an understanding of the required level of ecological protection must be established if protection goals for the environment are to be effective and sustainable. An overriding consideration is that the level of ecological protection provided by the groundwater quality guidelines must ensure that groundwater is of sufficient quality to support any current ecological groundwater use, and future uses which can reasonably be anticipated.

The appropriate level of protection was carefully considered in the development of soil quality guidelines, and the reader is directed to Section B 2.1 of the soil protocol for further details. In general the groundwater quality guidelines adopt the same protection goals as the corresponding soil quality guidelines. The most notable exception is based on land use considerations. Soil quality guidelines aim for a higher protection goal in areas that are expected to require a higher level of ecosystem functioning in order to sustain the activities normally associated with the land use (agricultural and residential) relative to land uses that are not expected to require the same level of ecosystem functioning (commercial and industrial). Due to the potential mobility of contaminants in groundwater, groundwater quality guidelines for all land uses are based on the level of protection for sensitive land uses. Further discussion is provided in Section B 3.2 of this document.

2.2 Selection of Ecologically Relevant Endpoints

The ecological assessment endpoint which represents the overall goal of groundwater quality guidelines is the maintenance of healthy populations of all biota that make up the ecosystems with which groundwater could come into contact. As is the case with soil quality guidelines, this assessment endpoint is determined based on measurement endpoints which are typically growth, reproduction, and survival metrics for relevant selected indicator species, often determined in laboratory tests. The selection of endpoints for groundwater quality guidelines closely follows that for soil quality guidelines, discussed in more detail in Sections B 2.2 to B 2.4 of the soil protocol.

3. Exposure Scenario Assumptions

3.1 Exposure Pathways and Receptors

Ecological receptors may in rare cases come into direct contact with contaminated groundwater but more commonly may be exposed to contaminants in groundwater after groundwater discharges into a surface water body, enters a dugout or well, or moves up into the vadose zone. Thus, a key first step in determining how ecological receptors may be exposed is identifying exposure pathways through which contaminants in groundwater may reach receptors. The starting point in this process is the set of exposure pathways and ecological receptor combinations in the soil protocol (see Section B 4.2 and Table 1 in that document).

Direct contact of plant roots with groundwater below the water table is only of concern for phreatophyte species (e.g., poplars, willows) which have the ability to draw water directly from the water table. The roots of non-phreatophytes (i.e., most plant species) do not penetrate the water table since they rely on oxygen in soil gas to support root respiration. Various processes can result in the movement of groundwater, potentially carrying contaminants, into the vadose zone where contaminants can come into contact with the roots of non-phreatophyte species.

This protocol does not consider stygobiota directly, and thus the possible exposure of exclusively groundwater dwelling invertebrates below the water table is not considered. However, the potential for contaminated groundwater to move upwards into the vadose zone and result in the exposure of soil dwelling invertebrates, and the roots of non-phreatophyte species, is considered, as well as the possibility of the roots of phreatophyte species being directly exposed to contaminated groundwater.

Overall, the ecological direct contact exposure pathway is considered valid for groundwater. Further information and discussion on this exposure pathway is provided in Section B 4.2 of this document.

The ingestion of contaminated soil and food exposure pathway is considered for deriving soil quality guidelines. However, it is expected that exposure to groundwater contamination via these pathways would be negligible in most cases, and these pathways are better addressed using soil quality guidelines.

Contaminated groundwater can discharge to surface water, where aquatic life (e.g., fish, aquatic invertebrates, and aquatic plants; freshwater or marine) may be exposed to contaminants. Thus this exposure pathway is considered valid for groundwater. Further information on this exposure pathway is provided in Section B 4.3 of this document.

Contaminated groundwater could potentially be accessed via a water well, a dugout, or after discharge to a surface water body and used for agricultural purposes (livestock watering or irrigation). Thus these routes of exposure are considered valid for groundwater. Further information on this exposure pathway is provided in Section B 4.4 of this document.

The exposure pathways considered in the development of groundwater quality guidelines, as compared to soil quality guidelines, are summarized below:

Table 1. Comparison of Groundwater and Soil Quality Guidelines Exposure Pathways

Groundwater Quality Guidelines	**Soil Quality Guidelines**
Protection of soil-dependent organisms (plants and invertebrates) from direct contact with contaminated groundwater	Protection of soil-dependent organisms (plants, invertebrates, and nutrient cycling processes – i.e., microbes) from direct contact with contaminated soil
Protection of aquatic life (surface water) from indirect contact with contaminated groundwater after discharge to surface water body	Protection of aquatic life (surface water) from contaminated soil after leaching into groundwater and discharging to surface water body
Protection of agricultural uses of water from contaminated groundwater (livestock, irrigation)	Protection of agricultural uses of water from soil contamination (livestock, irrigation)
	Protection of livestock and wildlife (mammals and birds) from ingestion of contaminated soil and food

3.1.1 Exclusion of Exposure Pathways

Individual jurisdictions may choose to allow the exclusion of the groundwater quality guidelines for certain exposure pathways in specific circumstances. The following notes may help to determine whether pathway exclusion is appropriate within a particular regulatory framework. Additional information is provided in relevant parts of Section B 4 of this document.

The groundwater contact exposure pathway considers the possibility of plants and soil invertebrates being exposed to groundwater contaminants. The likelihood of adverse effects is considered to be low for this exposure pathway at locations where the depth to groundwater is at least 3 m. Additional relevant information on plant rooting depths and invertebrate population density depth distribution is included in Section B 4.2.2 of this document.

The protection of aquatic life exposure pathway addresses contaminants moving laterally in groundwater and being discharged into a downgradient surface water body. As the distance to the nearest downgradient surface water body increases, the likelihood of adverse impacts on the aquatic life there decreases. However, the likelihood of adverse impacts at a downgradient water body will also depend on the fate and transport properties of a contaminant. For example, the vast majority (98.1%) of 647 groundwater plumes of dissolved hydrocarbons presented in Wiedemaier *et al.* (1999) are less than 274 m long, while chlorinated solvent plumes in excess of 3000 m have been reported (Lawrence Livermore National Laboratory, 1999). Section A 2.2.1 of the soil protocol suggests 10 km as being an appropriate distance to consider excluding this pathway on a non-chemical-specific basis, although individual jurisdictions may specify a different distance.

The protection of livestock watering and irrigation guidelines are relevant to agricultural land. Where a site is sufficiently far from the nearest agricultural land and future agricultural use is not likely, it may be possible to exclude this exposure pathway.

3.2 Land Use Considerations

Soil quality guidelines are developed based on a different set of assumptions for each of four standard land uses (agricultural, residential/parkland, commercial and industrial; see soil protocol Section B 5). Contaminants in groundwater tend to be more mobile than those in soil, and therefore the potential for contaminants to move from a less sensitive to a more sensitive land use is greater for groundwater than for soil. Accordingly, groundwater quality guidelines are not developed to be land use specific, but rather reflect a level of ecological protection appropriate to the most sensitive land use or to support any ecological groundwater use which can reasonably be anticipated.

4. Guidelines Derivation Process

The process for deriving groundwater quality guidelines for non-human biota, according to the key receptors and exposure pathways previously described is provided in this Section. Many of the models are derived from the corresponding models in the soil protocol, and where this is the case, it is noted for each model.

4.1 Literature Review and Data Requirements

The data requirements for deriving groundwater quality guidelines will generally be a subset of the data required for developing soil quality guidelines. It is anticipated that groundwater quality guidelines will commonly be derived in parallel with soil quality guidelines, and thus additional literature review work may not be required for groundwater quality guidelines. Additional information is provided in Section B 7.1 of the soil protocol.

When developing groundwater quality guidelines, it is important to have a good understanding of the environmental behaviour of the contaminant. However, in most cases the data to determine this will already have been collected as part of the literature review for developing soil quality guidelines.

Environmental groundwater quality guidelines will normally take existing guidelines for other media (e.g., soil quality guidelines, surface water quality guidelines) as their basis, and therefore will not typically require acquiring new toxicological data as part of the literature review.

4.2 Derivation of Groundwater Quality Guidelines for Groundwater Contact

The soil protocol includes Soil Quality Guidelines for Soil Contact (SQG_{SC}) by soil-dependant organisms (CCME, 2006). This exposure pathway considers the potential effects of soil contaminants on populations of terrestrial plants and soil invertebrates. The potential also exists for contaminants in groundwater to affect terrestrial plants and soil invertebrates.

As indicated in Section B 3.1, the only biota expected to be directly exposed to groundwater contaminants below the water table are phreatophyte plants (and stygobiota, which is not considered in this protocol). The vast majority of terrestrial plant species are not phreatophytes (i.e., their roots do not penetrate the water table). However, Tier 1 guidelines are intended to be conservative, and accordingly groundwater quality guidelines for groundwater contact by soil-dependant organisms ($GWQG_{GC}$) are developed for phreatophyte plants. The values so developed are assumed to be protective of all terrestrial plants and soil invertebrates immersed (temporarily) in contaminated groundwater. A possible Tier 2 approach for site-specific situations where phreatophytes are not present, and the main concern is the periodic inundation of terrestrial invertebrates and non-phreatophyte plant species with contaminated groundwater, is indicated in Section B 4.2.3.

The SQG_{SC} are developed based on plant and invertebrate toxicity tests conducted in soil. It is assumed (see Section 4.2.1, below) that plants and soil invertebrates are primarily exposed to, and sensitive to, the portion of the contaminant dissolved in pore water. The pore water concentration C_W (mg/L) corresponding to the SQG_{SC} (mg/kg), can be calculated as follows:

$$C_w = \frac{SQG_{SC}}{DF1} \qquad \text{(Equation B.4.1)}$$

Where DF1 is the dilution factor from the soil protocol groundwater models (Appendix C of the soil protocol) representing soil to porewater partitioning, and is calculated according to Equation A-2 in Appendix A of this document.

If the conservative assumption is made that phreatophyte species take all their water directly from the groundwater table or the capillary zone, then the corresponding groundwater quality guideline for groundwater contact by soil-dependent organisms ($GWQG_{GC}$), can be estimated by setting it equal to C_w, and hence:

$$GWQG_{GC} = \frac{SQG_{SC}}{DF1} \qquad \text{(Equation B.4.2)}$$

The SQG_{SC} for agricultural land is used to develop Tier 1 $GWQG_{GC}$ values for all land uses. This conservative assumption reflects the potential for groundwater to move off site into areas with land uses that differ from that of the site under consideration (Section B 3.3). Thus, Tier 1 $GWQG_{GC}$ values are the same for all land use classifications. However, different values may be calculated for coarse and fine-grained soils depending on data availability.

The Tier 1 model, developed above, for calculating the groundwater quality guideline for groundwater contact ($GWQG_{GC}$) is summarized in Appendix A. Parameter values are provided in Appendix B.

4.2.1 $GWQG_{GC}$ Based on Porewater Concentrations

Van Gestel *et al.* (1991) and Van Gestel and Ma (1988, 1990) have shown that the toxicity of chlorophenols, dichloroaniline, and chlorobenzenes to earthworms in soils differing in organic matter content is almost the same when expressed in terms of pore water concentration. Hulzebos *et al.* (1993) came to a similar conclusion in a study on the toxicity of a wide variety of compounds to lettuce, both in soil and in nutrient solution. Thus for some but not necessarily all chemicals, it appears that the toxicity to plants and soil invertebrates may be better predicted from soil pore water concentrations than from total soil concentrations.

In cases where the situation described in the preceding paragraph can be shown to exist, and where suitable and defensible data are available, there is an option to develop $GWQG_{GC}$ based on porewater concentrations measured in appropriate toxicity studies rather than partitioning from the SQG_{SC}. If this approach is taken, the procedures used to select and interpret data should follow the equivalent procedures provided in the soil protocol, as far as possible.

In particular, three methods are anticipated for developing $GWQG_{GC}$ based on porewater concentrations, which are, in order of preference:

- the Weight of Evidence Method;
- the LOEC Method; and,
- the Median Effects Method.

Section B 7.5 of the soil protocol provides details on how these methods are applied to develop the SQG_{SC} for soil. It is intended that $GWQG_{GC}$ values based on porewater concentrations should be developed paralleling Section B 7.5 of the soil protocol as closely as possible, though some deviations may be required as a result of the different contaminated medium.

4.2.2 Exclusion of the Groundwater Contact Exposure Pathway and Rooting Depth

Individual jurisdictions will make their own decisions concerning whether or not to allow the exclusion of this exposure pathway in circumstances consistent with their contaminated sites management framework. Some jurisdictions have previously made the management decision that the ecological soil and/or groundwater contact exposure pathways have limited relevance below 3 m and can be excluded below that depth. Available information on plant rooting depth and populations of soil invertebrates support this decision, as discussed below.

While extreme rooting depths have, on occasion, been recorded for particular plant species in very arid conditions (e.g., Canadell *et al*., 1996), available data support the conclusion that very few of the roots of most terrestrial plant species relevant to Canada grown in most conditions exceed a depth of 3 m. Most typical Canadian crop and pasture species have effective rooting depths of 1.5 m or less (Gerwitz and Page, 1974; Weaver, 1926; Weaver and Bruner, 1927). Effective root depth is defined as the depth from which a plant species draws the majority of its water. Deeper rooted Canadian crop and pasture species include alfalfa, brome grass, red clover, sugar beet and safflower. But even in these species only a very small fraction, if any, of the root system extends below 3 m (Borg and Grimes, 1986; Dardanelli *et al*., 1997; Johnston *et al*., 2002; Weaver, 1926).

The rooting depths of trees vary with soil conditions and species. Canadian tree species with relatively shallow root systems include aspen, balsam poplar, white birch, black spruce, white spruce and tamarack (Burns and Honkala, 1990a,b). Species that are typically deeper rooted include lodgepole pine and jack pine. However, as with the crop and pasture species, only a very small fraction, if any, of the root system extends below 3 m under typical conditions (Bannan, 1940; Burns and Honkala, 1990a; Horton, 1958; Strong and La Roi, 1983).

Canadian phreatophyte species are of particular relevance to Tier 1 $GWQG_{GC}$ guidelines. Quantitative data are somewhat limited, however Burns and Honkala (1990b) consider the North American *Populus* species (poplars and aspen; n=8) and *Salix* species (willows; n=1) species that they review to be relatively shallow rooted. Canadell *et al*. (1996) in an extensive review of the worldwide literature on maximum rooting depth found a maximum value of 2.2 m for the rooting depth of one *Salix* species, and maximum values in the range of 1.9 m to 2.9 m for four *Populus* species.

The limited available data on soil invertebrate depth distributions also support an exclusion depth of 3 m. Startsev and Battigelli (2008) investigated the vertical distribution of soil invertebrates in two undisturbed soils in Alberta. These authors found that the majority of soil invertebrates (>85% of the invertebrates found) were in the top 50 cm, while >95% were in the top 1.5 m of the soil profile. Thus only a very small fraction of the total soil invertebrate population would be expected to be present at depths below 3 m.

Overall, therefore, it appears that the vast majority of plant roots and the vast majority of soil invertebrates are present in the top 3 m of soil and to exclude this exposure pathway on a Tier 2 basis would be scientifically justifiable for contaminants deeper than 3 m.

Due to the mobility of groundwater, it may also be necessary to consider not only the depth to groundwater at the remediated site, but also the potential for the depth to be shallower at nearby properties.

4.2.3 Conceptual Model for Non-Phreatophyte Plant Species

The vast majority of Canadian plant and crop species are not phreatophytes. Where the presence of phreatophyte species can confidently be excluded due to site-specific conditions (phreatophytes are typically associated with riparian habitats), there may be value in considering an alternative model for plant and invertebrate exposure on a site-specific (i.e., Tier 2) basis. The remainder of this sub-section describes the "Multiple Inundation Model", which may be useful in this regard.

For non-phreatophyte plant species to be exposed to contaminants in groundwater, some mechanism must be postulated for contaminants in underlying groundwater to migrate into the vadose zone. The most plausible mechanism may be seasonal inundation of the vadose zone by fluctuating groundwater elevations.

Groundwater inundation is assumed to occur once per season, and the groundwater level is assumed to briefly go right up to ground surface (unlikely, but at least conservative, and this assumption significantly reduces model complexity).

During a single, brief, inundation event (ignoring any associated groundwater dilution), groundwater with a contaminant concentration of C_w (mg/L), rises into the vadose zone and then retreats. The maximum possible resulting soil concentration can be estimated by assuming that all the contaminant mass transported by the rising groundwater remains in the vadose zone, using the following equation:

$$C_S(0) = \frac{C_w \times n}{\rho_b} \qquad \text{(Equation B.4.3)}$$

Where:

$C_s(0)$	=	contaminant concentration in vadose zone soil immediately after inundation and drainage (i.e., at time t=0) (mg/kg)
C_w	=	contaminant concentration in groundwater, assumed to be equal to vadose zone porewater concentration during inundation (mg/L)
n	=	total porosity of vadose zone soil (dimensionless)
ρ_b	=	bulk density of soil in the vadose zone (dry basis) (g/cm^3)

Now, consistent with the soil protocol, the contaminant mass in the vadose zone is assumed to undergo first order decay (biodegradation). At the end of one year, the soil concentration will have decreased to:

$$C_S(1) = C_S(0)e^{-L_{us} \times 1} \qquad \text{(Equation B.4.4)}$$

Where:

$C_s(1)$	=	contaminant concentration in vadose zone soil one year after inundation and drainage (i.e., at time t=1) (mg/kg)
L_{us}	=	decay constant in the unsaturated zone (year^{-1})

However, at the end of one year, we assume another similar inundation, and thus the concentration in the vadose zone increases to:

$$C_S(1+) = C_S(0)e^{-L_{us}\times 1} + C_S(0)$$

or:

$$C_S(1+) = C_S(0)\left(1 + e^{-L_{us}\times 1}\right) \quad \text{(Equation B.4.5)}$$

Where:

$C_s(1+)$ = contaminant concentration in vadose zone soil one year after inundation and drainage and a second inundation (mg/kg)

After several years, with successive annual inundations and continuing degradation, the concentration in the vadose zone becomes:

$$C_S(n) = C_S(0)\left(1 + e^{-L_{us}\times 1} + e^{-L_{us}\times 2} + e^{-L_{us}\times 3} + \ldots\right) \quad \text{(Equation B.4.6)}$$

Where:

$C_s(n)$ = contaminant concentration in vadose zone soil after n years of annual inundations (mg/kg)

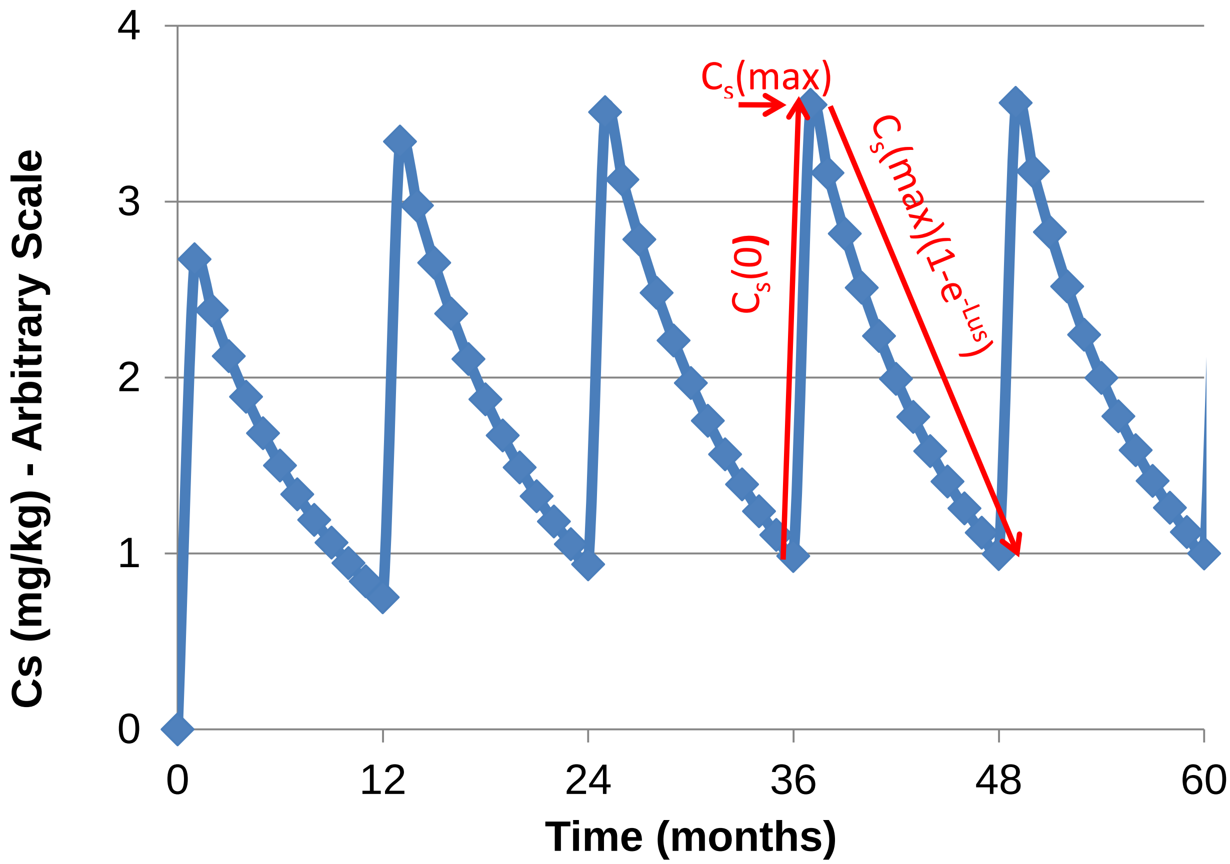

Figure 2: Example Graph of Soil Vadose Zone Concentration in Multiple Inundation Model

Figure 2 provides an example of the soil vadose zone concentration changing with time in the multiple inundation model. In this example, there are annual inundations and the half-life of the contaminant is 0.5 years, corresponding to L_{us} = 1.386 year^{-1}. This example shows how the concentration immediately after inundation increases, then reaches a maximum value, such that the contaminant lost due to degradation in one year is equal to the contaminant mass added in each inundation. This will occur at a concentration C_s(max) where:

$$C_S(\max) \times \left(1 - e^{-L_{us} \times 1}\right) = C_S(0) \quad \text{(Equation B.4.7)}$$

Where:

C_s(max) = maximum soil concentration in vadose zone (mg/kg)

Combining equations B.4.3 and B.4.7 and rearranging gives:

$$C_S(\max) = \frac{C_w \times n}{\rho_b \times \left(1 - e^{-L_{us} \times 1}\right)} \quad \text{(Equation B.4.8)}$$

And then the groundwater guideline protective of the soil contact pathway can be calculated as follows:

$$GWQG_{GC} = SQG_{SC} \times \left(\frac{\rho_b \times \left(1 - e^{-L_{us} \times 1}\right)}{n} \right) \quad \text{(Equation B.4.9)}$$

More generally, with a time T between each inundation, the equation becomes:

$$GWQG_{GC} = SQG_{SC} \times \left(\frac{\rho_b \times \left(1 - e^{-L_{us} \times T}\right)}{n} \right) \quad \text{(Equation B.4.10)}$$

Where:

$GWQG_{GC}$ = groundwater quality guideline protective of groundwater contact with plants and soil invertebrates (mg/L)

SQG_{SC} = soil quality guideline protective of soil contact with plants and soil invertebrates (mg/kg)

T = time between inundations (years)

This equation is referred to as the "Multiple Inundation Model".

4.2.4 Summary of $GWQG_{GC}$ derivation process

Groundwater quality guidelines for groundwater contact by soil-dependent organisms is based on the conservative assumption that roots of phreatophyte species may be permanently immersed in, and drawing from, contaminated groundwater. It is expected that plants and invertebrates periodically inundated by contaminated groundwater will also be protected using the same phreatophyte conceptual model. The $GWQG_{GC}$ is calculated either from partitioning of the SQG_{SC} for agricultural land using equations described in section 4.2, or based directly on an evaluation and analysis of porewater toxicity data described in section 4.2.1. The groundwater contact exposure pathway may be excluded on a Tier 2 basis in cases where the depth to groundwater reasonably excludes the possibility of contact with roots and invertebrates as described in section 4.2.2. In situations where groundwater is expected to come into contact with roots and invertebrates (e.g., water table depth ≤ 3m), but phreatophytes are not present, relief from Tier 1 may be achieved by calculating a site-specific remediation objective (i.e., Tier 2) to protect plants and invertebrates using the multiple inundation model described in section 4.2.3.

4.3 Derivation of Groundwater Quality Guidelines for the Protection of Aquatic Life

Contamination present in groundwater can migrate laterally. If there are surface water bodies (streams, rivers, lakes, etc.) nearby then aquatic life in these surface water bodies may be affected by the contamination, particularly if there is a permeable zone connecting the contamination with the surface water body. The purpose of groundwater quality guidelines for the protection of aquatic life is to determine groundwater concentrations that are sufficiently low that, allowing for attenuation in the aquifer, the concentration of groundwater discharging into a surface water body meets the Canadian Water Quality Guidelines for the Protection of Aquatic Life (CCME, 1999).

For purposes of developing generic guidelines, it is assumed that the surface water body is located 10 m away from the contaminated groundwater. While it is recognized that groundwater may be diluted within an initial mixing zone once it reaches a surface water body, a dilution factor for mixing in the surface water body is not applied for generic guideline development due to the site-specific nature of this process and the variance in policy decisions across Canadian jurisdictions regarding dilution within the receiving environment.

Groundwater quality guidelines for this exposure pathway are calculated based on the model for centreline plume concentrations provided in Equation 6 of Domenico (1987) (the "Domenico Model"). The equation has been modified to reflect the conservative assumption that there is no dispersion in the vertical (z) direction. The model estimates the decrease in groundwater contaminant concentration over 10 m of lateral travel by considering downgradient contaminant transport including dispersion in the longitudinal (x) and lateral (y) directions, and first order biodegradation. The model is consistent with the corresponding CCME model for soil quality guidelines.

Various authors, including West *et al*. (2007) and OMOE (2009) have noted that the Domenico Model is an approximate solution, and that exact solutions exist. However this issue has been considered by CCME, and it has been determined that the approximations involved are minor in relation to the overall uncertainties involved in developing groundwater quality guidelines, and accordingly, the use of the approximate Domenico model is deemed appropriate.

The model is described in detail in Appendix A, and model parameters are included in Appendix B. This exposure pathway is evaluated for soluble organic contaminants only. Separate groundwater quality guidelines are calculated for the protection of freshwater and marine life ($GWQG_{FL}$ and $GWQG_{ML}$) if the corresponding Canadian water quality guidelines are available (CCME, 1999). If no Canadian Water Quality Guideline exists, then guidelines from other jurisdictions (i.e., Canadian or international), offering a similar level of protection, may be used.

The groundwater quality guidelines for the protection of aquatic life are independent of the land use classification; however, guidelines are calculated separately for coarse and fine-grained soils to reflect the differences in groundwater transport between different soil types.

4.3.1 Time Dependant vs. Steady State Model Versions

Domenico (1987) includes both time dependant and steady state versions of his model. After sufficiently long times, the two model versions give identical results. The soil protocol (CCME, 2006) used the time dependant version, and hence gives groundwater concentrations as a function of time. Consideration was given to the choice of steady state vs. time dependant models for calculating groundwater guidelines. Advantages of using the steady state model include a simpler equation to work with, and the removal of the potential for using an inappropriately short time for evaluation. Advantages of using the time dependant model include the option for jurisdictions to limit the upper bound of time considered in the case of very highly retarded (i.e., very slow moving) contaminants in the case that degradation rates are assumed to be zero. This issue was considered at length by CCME, and it was decided to use the time dependant version of the model in this document (Appendix A). Care must be taken to input a sufficiently long time to be sure of getting a steady state result, unless a jurisdiction decides to explicitly limit the maximum time considered.

4.3.2 Depleting Source vs. Non-Depleting Source Model Versions

Transport of groundwater contaminants, by definition, removes contaminant mass from the source area. Thus, unless there is an external input of contaminant to the source area, soil and/or groundwater source area concentrations will tend to decrease over time. Degradation may also decrease source area concentrations over time. However, the model used in this document to calculate generic groundwater quality guidelines does not consider source depletion (i.e., it assumes an infinite source scenario) for the reasons indicated below.

Groundwater contamination is frequently sourced from soil contamination. Mass balance calculations allow an estimate to be made of the (first order) rate of decrease of a soil source due to leaching from infiltrating precipitation. In most cases, the time taken for the soil source to decrease significantly is greater than the time taken to achieve a steady state groundwater concentration 10 m downgradient from the source, and also typically greater than the duration of the acute or chronic tests on which aquatic life water quality guidelines are based. Generic groundwater quality guidelines are intended to protect water quality at all future times, and therefore it would not be appropriate to include source depletion, which would result in higher guideline values, in the calculation of a generic groundwater quality guideline.

In addition, a depleting source model may not be conservative in the case of NAPL being present.

In the case where a groundwater plume is present, but there is no contamination in soil (possibly as a result of the complete excavation of the soil source and replacement with clean soil), a depleting source model may be appropriate. However, such a model would be applied as part of a site-specific risk assessment, and does not form part of the calculations for generic guidelines.

4.3.3 Guidance on Determining a Groundwater Degradation Rate

The groundwater model for the protection of freshwater aquatic life described in this section and provided in Appendix A assumes that organic contaminants in groundwater are subject to first order degradation. The degradation rate is input into the model as a degradation half-life.

The groundwater degradation rate for organic chemicals is not a constant, but may vary over orders of magnitude depending on a wide range of site-specific factors including the type and population density of bacteria present, temperature, availability of nutrients and availability of terminal electron acceptors (oxygen, nitrate, sulphate etc.).

Given the site-specific and variable nature of groundwater degradation rates, any rate value used in the development of Tier 1 (generic) guidelines must be sufficiently conservative to apply to the vast majority of sites. In practice this will often mean giving careful consideration to the lowest available degradation rates in the literature, taking into account both aerobic and anaerobic studies.

A good starting point in this process is to determine whether there are any groundwater degradation rates available from regulatory agencies. These should not necessarily be accepted at face value, however, but rather the underlying data should be reviewed, where possible.

In the absence of values available from regulatory agencies, it will be necessary to conduct a literature search and identify studies with potentially relevant data. It is important that all data be critically screened for relevance of experimental design. There are many different laboratory and field techniques that can be used to develop values for groundwater degradation rates. Some of these are summarized and discussed in SABCS (2006). General information on types of degradation data is provided below, with comments, in order of preference.

1. Field data. Typically, degradation rate data interpreted from actual field studies are preferred over other data types, particularly if the data are appropriate for Canadian groundwater conditions. Such studies are the most relevant as they relate to actual conditions in groundwater. Ideally, such studies would not involve addition of any amendments to the groundwater, and would include measurement of factors relevant to biodegradation rates, including a determination of whether subsurface conditions are aerobic or anaerobic. However, the time and expense involved in conducting such studies means that they are only available for a limited range of compounds.

2. Laboratory data conducted with field-collected groundwater samples or sediment slurries. Such studies aim to replicate subsurface conditions in the laboratory. Ideally, no amendments would be added to the samples, and incubation would occur at cool temperatures relevant to groundwater conditions and possibly in the dark. Ideally, both aerobic and anaerobic conditions would be investigated.

3. Other relevant laboratory data. Where data from groups (1) and (2) are not available, there may be other relevant degradation data from laboratory studies. As a minimum such studies should not be amended with nutrients or bacteria. Ideally, studies would be conducted under conditions of dark and cold and investigate both aerobic and anaerobic conditions.

For some organic chemicals, a majority of the degradation data are from short term experiments (a few hours to a few days), conducted with acclimated bacteria, and excess nutrients and oxygen. These studies are typically designed to answer the question “can this chemical be made to degrade under optimum conditions”. The degradation rates obtained from such studies are of little relevance to degradation rates in groundwater, and should not normally be used to develop groundwater degradation rates.

If data are available consistent with categories (1), (2), or (3) above, it may be possible to develop a value for groundwater degradation rate. In general, it will be appropriate to use the lowest degradation rate available. However, professional judgement will still be required to determine whether the rate is appropriate and reasonably conservative for the range of conditions encountered at Canadian sites (including sites with anaerobic conditions). Additional factors to consider could include any qualitative or semi-quantitative information from field studies that would tend to support or refute degradation being active in groundwater. Another factor to consider would be whether the contaminant might inhibit bacterial activity at the calculated groundwater quality guideline value, either directly via toxicity, or indirectly by generating an anaerobic groundwater plume.

4.3.4 Applicability of Groundwater Degradation Rates

Groundwater quality guidelines calculated using the model described in this section and provided in Appendix A are based on the assumption that organic contaminants in groundwater may be subject to first order degradation (Domenico, 1987). Guidance on assessing available data to develop an appropriate, conservative degradation rate was provided in Section B 4.3.3, above. If suitable data are not available, or if available data indicate that degradation does not occur, then a degradation rate of zero (or infinitely long half-life) would be input into the model and degradation would not be considered.

While not directly relevant to the development of generic groundwater quality guidelines, there are also some site-specific considerations that may be relevant in the determination of whether to apply degradation. These could include:

- The presence of other groundwater contaminants (e.g., salts) that might inhibit bacterial activity.
- The presence of a co-contaminant that may be preferentially degraded.
- The presence of an anaerobic groundwater plume that could restrict biological degradation.
- Unusually low levels of key nutrients (e.g., phosphate) in the groundwater in cases where bacteria are known to require them for degradation of the particular chemical.

Individual jurisdictions will make their own decisions concerning whether or not considering contaminant degradation in the calculations for generic groundwater quality guidelines is consistent with their contaminated sites management framework. Groundwater degradation can be excluded from the generic groundwater quality guidelines simply by adopting the surface water quality guideline for the protection of aquatic life as the groundwater quality guideline.

4.4 Derivation of Groundwater Quality Guidelines for Protection of Livestock Watering and Irrigation

Water wells and dugouts are potential sources of groundwater used for livestock watering or irrigation. A water well or dugout can potentially be installed or constructed at any location, including within, or immediately adjacent to, a groundwater contaminant source. It will therefore not generally be possible to be confident of any minimum lateral separation between groundwater contamination and a well or dugout. Thus, no minimum groundwater attenuation can be assumed before the receptor is exposed to the groundwater. Accordingly, the groundwater quality guidelines for the protection of livestock watering ($GWQG_{LW}$) and irrigation ($GWQG_{IR}$) are numerically equal to the Canadian Water Quality Guidelines for the Protection of Agricultural Water Uses (Irrigation and Livestock Water) (CCME, 1999).

4.5 Consideration of Additional Exposure Pathways

It is anticipated that in most situations, the exposure pathways described above will be sufficient for the development of environmental groundwater quality guidelines. However, other exposure pathways exist, such as dermal contact of wildlife with contaminated water. If the literature review indicates that another exposure pathway may be of particular concern for a given chemical, then this pathway should be evaluated. Specific guidance on the evaluation of additional exposure pathways is not provided herein at this time; where possible, methods published by regulatory agencies such as Environment Canada or United States Environmental Protection Agency should be applied.

PART C

1. Derivation of Human Health Groundwater Quality Guidelines

1.1 Introduction

As detailed in Section C 1.1 of the soil protocol, the derivation of human health groundwater quality guidelines involves:

- assessing the toxicological hazard or risk posed by a chemical
- determining estimated daily intake (EDI) of that chemical, unrelated to any specific contaminated site (i.e., "background" exposure)
- defining generic exposure scenarios for the residential/agricultural and commercial/industrial land uses
- integrating exposure and toxicity information to set groundwater quality guidelines. These guidelines must ensure that total exposure to a contaminant (EDI and site-related exposure) will present no appreciable human health risk.

The steps employed to derive groundwater quality guidelines are similar to those used for site-specific risk assessment, and are subject to several sources of uncertainty, detailed in Section C 1.3 of the soil protocol. Exposure pathways are evaluated using mathematical models. The input values for the models depend on the choice of sensitive human receptor, exposure duration, frequency, and intensity. Evaluation of indirect exposure pathways also requires input values representing physical characteristics of the site, which are affected by the soil type classification. Simplified models were deliberately chosen to represent the indirect exposure pathways to limit the number of assumed input parameters; at a site-specific level, more complex models, along with detailed site-specific information, can provide more precise modelling results.

The potential exposure pathways considered in the development of human health groundwater quality guidelines are:

- Ingestion of groundwater used for potable water (along with dermal and inhalation exposures resulting from domestic use of groundwater)
- Indoor vapour inhalation of contaminants volatilized from groundwater and migration into indoor air (applies to volatile contaminants only)

The development of site-specific objectives via limited modification of the generic guidelines, or the development of objectives using risk assessment, permits the flexibility required to remove or to add exposure pathways or to use site-specific models to develop more accurate values.

1.2 Guiding Principles

The guiding principles (listed below) for the derivation of generic groundwater quality guidelines protective of human health reflect the principles adopted by CCME for contaminated sites (adapted from CCME, 2006):

1. There should be no appreciable risk to humans from contamination at a contaminated site. Within the allowable land uses, there should be no restrictions as to the extent or nature of the interaction with the site. All activities normally associated with the intended land use should be free of any appreciable health risk.
2. Guidelines are based on defined, representative situations. Deriving numerical guidelines necessitates defining specific scenarios within which the exposure likely to arise on the site can be predicted with some degree of certainty.
3. Guidelines are derived by considering exposure through all relevant pathways. The total exposure from soil, air, water, food and consumer products is considered in the development of guidelines.
4. To ensure that the guidelines do not limit the application of a site, the defined exposure scenarios are usually based on the most sensitive receptor to the chemical, and the most critical health effect.
5. Guidelines should be reasonable, workable and usable. Guidelines are developed by applying scientifically derived information, backed by professional judgement where data gaps occur. Occasionally, defined exposure-based procedures produce numerical guidelines either far below background levels of naturally occurring substances in the groundwater, or below practical quantitation limits. When this occurs, guidelines cannot be below background levels, and provisional guidelines should be established based on background groundwater concentrations.

1.3 Investigation of Contaminant Toxicology

Contaminant toxicology is discussed in detail in Section C 2 of the soil protocol. The toxicity of contaminants is represented using Toxicity Reference Values (TRVs) developed or endorsed by Health Canada. Specifically, for threshold substances, a Tolerable Daily Intake (TDI) and/or Tolerable Concentration (TC) is used to evaluate chemical toxicity to humans; for non-threshold substances, a Risk-Specific Dose (RSD) and/or Risk-Specific Concentration (RSC), derived from a Slope Factor (SF) or Inhalation Unit Risk (IUR) is used.

1.4 Exposure to Contaminants

Section C 3 of the soil protocol provides information on addressing mixtures of chemicals and for establishing the Estimated Daily Intake (EDI) to represent background exposure to a contaminant; this information is not repeated herein.

1.5 Relationships between Groundwater Quality Guidelines and Soil/Water Guidelines

The groundwater guidelines based on the ingestion of groundwater used for potable water are usually based on the Guidelines for Canadian Drinking Water Quality (GCDWQ) (see Section C 3 below). While the GCDWQ were developed for water systems at the point of exposure, they apply for groundwater and surface water used as a domestic water source. Where groundwater is or may potentially be used as a source of potable water, and chemical concentrations exceed the GCDWQ as a result of site contamination, groundwater management will be required. Options may include, but are not limited to: aquifer remediation, drinking water treatment, alternate water supply provision, long term monitoring and/or administrative controls (i.e., tracking of site conditions on land title or equivalent).

Groundwater guidelines based on volatilization of contaminants to indoor air are not explicitly based on any other guidelines, but are closely related to Canadian soil quality guidelines calculated for the same exposure pathway. Both soil and groundwater quality guidelines for the protection of indoor air are calculated using the same vapour transport model and model input parameters (see Appendices A and B).

2. Exposure Scenarios and Pathways

The exposure scenarios and pathways used for the derivation of groundwater quality guidelines are based on those applied for Canadian soil quality guidelines. The reader is referred to Section C 4 of the soil protocol (CCME, 2006) for a more in-depth examination of the exposure scenarios and pathways; a brief summary is provided below.

2.1 Assumptions about Exposure

Groundwater quality guidelines for the protection of human health are developed to ensure that contaminants present at the guideline concentration will not result in adverse human health effects. For the purpose of guideline development, CCME assumes a chronic exposure scenario (i.e., lifetime exposure to a remediated site). This is a conservative assumption, which helps ensure that no limitations will exist with respect to the use of the land or groundwater.

Guidelines are developed to consider potential human exposure pathways within a multimedia context. Humans are assumed to be potentially exposed to 5 different media at contaminated sites: soil, water, air, food and consumer products. Direct exposure to contaminated groundwater is expected to arise primarily from ingestion of contaminated groundwater.

Cross-media transfer of a chemical from contaminated groundwater to other media can result in indirect exposure to groundwater contaminants. The groundwater quality guidelines include consideration of the volatilization of contaminants from groundwater and migration into indoor air.

If the defined exposure scenario used in developing the generic guidelines is thought to be inappropriate for the particular site to be remediated, the generic guidelines may be modified within limits through the setting of site-specific objectives, which may involve the removal, addition or calibration of exposure pathways to more accurately represent the exposure scenario present at a specific site.

2.1.1 Threshold Contaminants

For threshold contaminants, the guidelines consider that exposure occurs from multiple media at the contaminated site, as well as background exposure as represented by the EDI. Guidelines are derived by calculating the residual tolerable daily intake (RTDI) as the difference between the TDI and EDI (RTDI = TDI – EDI), then allocating the RTDI between the primary exposure media. No single medium should deplete the entire tolerable daily intake or even the entire residual tolerable daily intake. By default, 20% of the RTDI is allocated to each of the five primary media (air, water, soil, food and consumer products), as shown in Figure 3. This allocation is implemented by multiplying the RTDI by an "allocation factor" (AF), which by default has a value of 0.2 (20%).

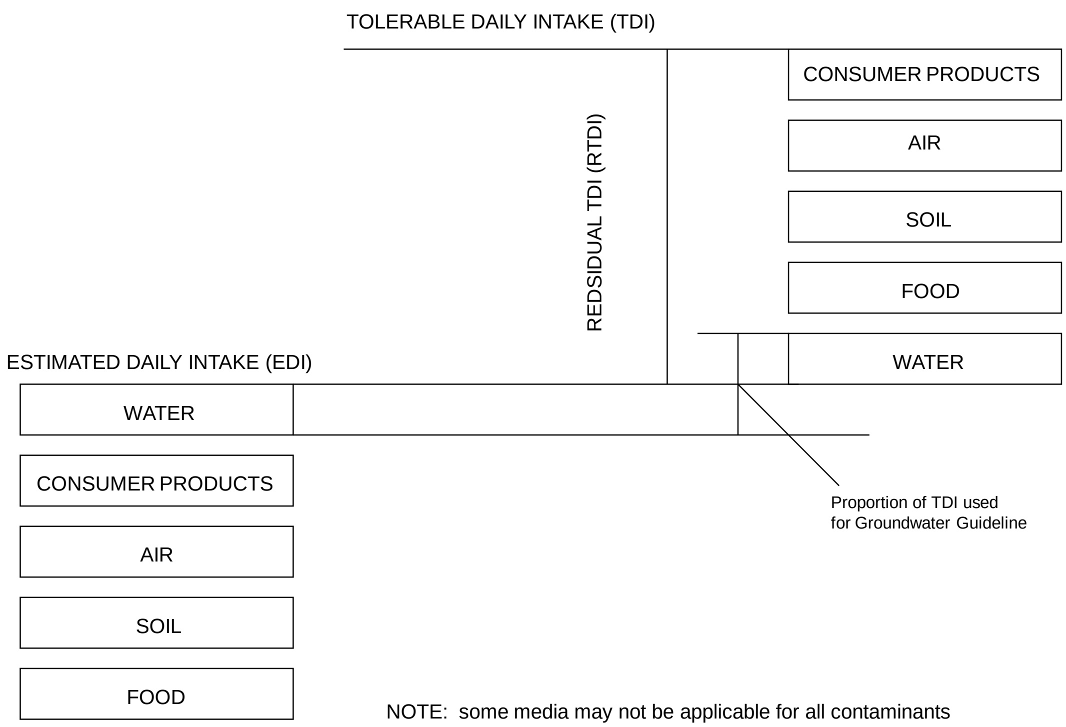

Figure 3: Conceptual Derivation of the Groundwater Guideline for Threshold Substances from the Multimedia Exposure Assessment and Assumed Allocation Factor from the Residual Tolerable Daily Intake

Inhalation exposures may be evaluated using a TC instead of the TDI. In this case, a similar approach is applied, where the background concentration in air is subtracted from the TC and the resulting "residual TC" is multiplied by the AF.

Depending on their physical and chemical properties, some groundwater contaminants may not normally be present in all four of the remaining media (air, soil, food and consumer products). For example, high molecular weight hydrocarbons exhibit very low volatility and, as a result, the contribution of air to overall human exposure may be insignificant. If defensible contaminant-specific evidence exists demonstrating that the contaminant does not occur in a given medium, the RTDI may be distributed amongst fewer media and the allocation factor may be increased from 20% to a value given by:

$$AF = 1 / (\text{number of applicable exposure media}) \qquad \text{(Equation C.2.1)}$$

For some chemicals, the EDI may be greater than the TDI, resulting in an RTDI of 0 or less. In these circumstances, Health Canada should be consulted to determine an appropriate approach for developing a groundwater quality guideline.

2.1.2 Non-threshold Contaminants

Groundwater quality guidelines for non-threshold substances, like soil guidelines, are derived based on a specified incremental risk above background from remediated groundwater at the guidelines concentration. Guidelines are derived for both a 1×10^{-5} and a 1×10^{-6} incremental risk; individual jurisdictions may apply guidelines based on either one of these risk levels.

2.2 Absorption of Chemicals into the Body

As discussed in Section C 4.2 of the soil protocol (CCME, 2006), the health risk posed by a particular exposure depends on the absorbed dose; where the critical toxicological study has used a different exposure medium than that under investigation, a relative absorption factor (RAF) may be applied to account for the difference in absorption of the contaminant by the body in the two different media if adequate supporting information is available.

However, direct exposure to groundwater is addressed using Guidelines for Canadian Drinking Water Quality or Source Guidance Values for Groundwater (see Section C 5.3.2 of the soil protocol), and TRVs used to address the vapour inhalation pathway are normally based on air; therefore it is anticipated that groundwater quality guidelines will almost always be derived using a RAF of 1.

2.3 Receptors and Exposure Pathways

The development of human health groundwater quality guidelines considers protection of potable groundwater and indirect exposure through inhalation of vapours migrating into indoor air.

Guidelines for the protection of potable groundwater are based on the Guidelines for Canadian Drinking Water Quality or on Source Guidance Values for Groundwater developed by Health Canada (see Section C 3.1 of this document). While these guidelines primarily address the ingestion of water, recent guidelines published by Health Canada have also included consideration of dermal and inhalation contact with water while bathing and showering. Since the values developed by Health Canada are applied directly, there is no need for additional receptor characteristics. The use of a groundwater aquifer as a source of domestic water is not considered to be dependent on land use; however, the guideline for this exposure pathway may be excluded if deemed appropriate by the implementing authority.

The volatilization of groundwater contaminants and subsequent migration through soil and into indoor air is evaluated for volatile chemicals. Guidelines are calculated separately for two scenarios: an agricultural/residential guideline reflecting an individual residing at the site full-time, and a commercial/industrial scenario reflecting a typical occupational exposure scenario. Individual jurisdictions should be consulted regarding whether the agricultural/residential guideline can be excluded at commercial/industrial sites, and if so if there are any offset requirements to account for potential migration to more sensitive neighbouring sites.

If toxicity is evaluated using a TC or RSC, receptor characteristics are unnecessary; if a TDI or RSD is used, then a toddler receptor is used to calculate the generic guidelines using the characteristics from the soil protocol (an adult may be used for the calculation of site-specific guidelines for industrial sites or other sites where children are not expected to be present).

3. Human Health Guideline Derivation Process

As discussed in Section C 2, human health groundwater quality guidelines are derived for the protection of potable groundwater and indirect exposure via indoor vapour inhalation. These two exposure pathways are detailed in Sections C 3.1 and C 3.2 below; the equations and model input parameters are summarized in Appendices A and B, respectively.

3.1 Guidelines for the Protection of Potable Groundwater Sources

Groundwater quality guidelines for the protection of potable water ($GWQG_{PW}$) are adopted directly from the latest version of the Guidelines for Canadian Drinking Water Quality (Health Canada, 2010a). In the absence of an official drinking water quality guideline, a Source Guidance Value for Groundwater developed by Health Canada can be used (see section 5.3.2 of soil protocol).

Some jurisdictions may allow the exclusion of this exposure pathway at sites where groundwater is not likely to be used as a drinking water source. While the specific criteria depend on the jurisdiction, this exposure pathway is often excluded if:

- municipal bylaws prohib water wells for potable water use
- shallow groundwater is naturally non-potable, or
- there is a lack of hydrological connection between contaminated soils and groundwater aquifers with sufficient recharge for potable water use.

3.2 Guidelines for the Protection of Indoor Air Quality

Contamination of indoor air by volatilization from contaminated groundwater is a potentially critical pathway of exposure for volatile organic chemicals. Therefore, human health groundwater quality guidelines for volatile organic chemicals must be protective of indoor air quality.

The relationship between contaminant concentrations dissolved in groundwater and in the vapour phase is evaluated based on the Henry's Law constant for the chemical, which in turn is a function of vapour pressure and water solubility.

Once in the vapour phase, volatile organic compounds migrate into buildings via diffusion and advection caused by barometric pressure differentials between the soil gas and the indoor air. The migration into indoor air is also a function of a variety of factors including soil type, depth or distance of contamination from the building foundation, type of building foundation, the building air exchange rate, and building dimensions. The processes are evaluated using an analytical model developed by Johnson and Ettinger (1991); further details are provided in Appendix E of the soil protocol (CCME, 2006). Other factors not explicitly addressed by the model, including heterogeneous stratigraphy, variation in atmospheric pressure, temperature, precipitation and soil moisture may also affect vapour migration into buildings; the default model assumptions selected are believed to be protective of normal variations in these site parameters in most cases.

One assumption in the calculation of groundwater quality guidelines for the protection of indoor air quality ($GWQG_{IAQ}$) using Johnson and Ettinger (1991) is that the source of contamination is not very close to the building. **There must be a minimum of 1 metre of clean soil between the capillary fringe and the building foundation at *your site* in order to use the $GWQG_{IAQ}$ for all land uses (see Figure 4)**. Seasonally high water tables should be taken into consideration to ensure that there is a minimum 1 metre separation distance to the capillary fringe across seasons. If there is not 1 metre separation, it is recommended that the generic $GWQG_{IAQ}$ calculated using the Johnson and Ettinger model not be used. Instead, it is recommended that the indoor air pathway be evaluated using a Tier 2 approach that uses a default attenuation factor of 0.01 for a commercial building or 0.03 for a residential building. Details on the development and use of the default attenuation factors are presented in Appendix C of A Protocol for the Derivation of Soil Vapour Quality Guidelines for Protection of Human Exposures via Inhalation of Vapours (CCME, 2014). Part A section 3.3 of CCME (2014) outlines additional assumptions that would invalidate the generic indoor air pathway (e.g., tall buildings, preferential pathways).

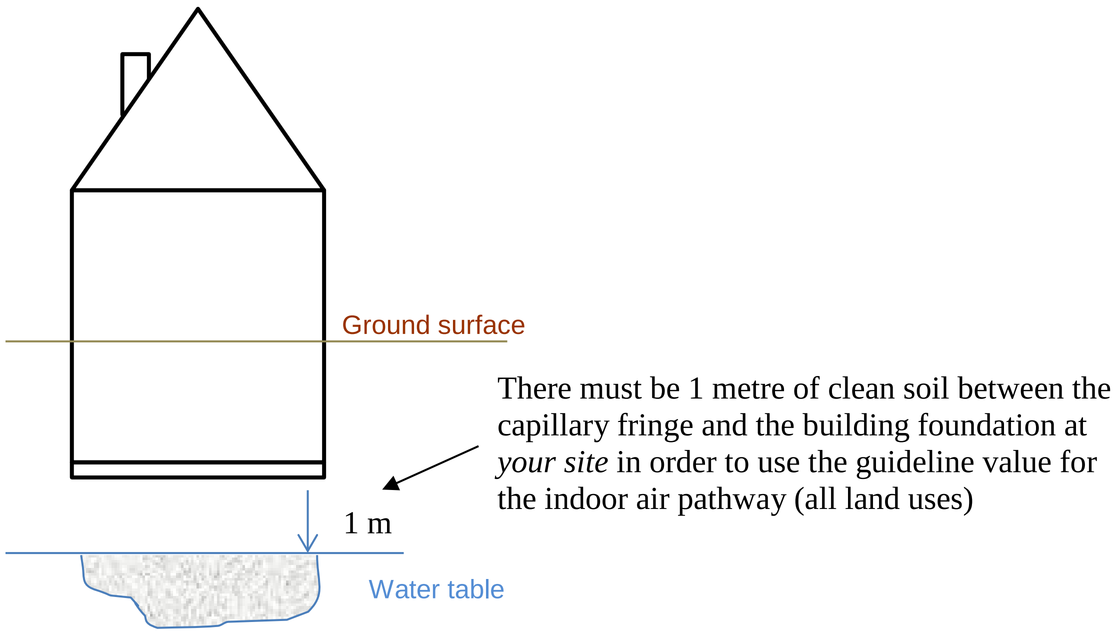

Figure 4. Source to building conditions for applying indoor air quality guideline

It should be noted that the Canada-wide Standard for Petroleum Hydrocarbons in Soil (CCME, 2008b) includes multiplication by an adjustment factor of 10 for soil quality guidelines for petroleum hydrocarbons (vapour inhalation pathway). While this adjustment factor includes consideration of biodegradation, it primarily reflects an adjustment for the conservatism in the soil to vapour partitioning relationship for petroleum hydrocarbons based on empirical data. An adjustment factor of 10 is employed in the calculation of $GWQG_{IAQ}$ for petroleum hydrocarbons for all land uses (an adjustment factor of 1 is assigned to non-PHCs, for example, chlorinated compounds). If there is not 1 m of clean soil between the contaminant source and building, use of either the 10 x adjustment factor or the Johnson and Ettinger model used to derive the $GWQG_{IAQ}$ (see above) is not considered appropriate. A Tier 2 approach for PHCs when the source is < 1 m to a building should not include generic bioattenuation factors (e.g., 10 x) for PHCs.

Some jurisdictions may allow this exposure pathway to be eliminated if there are no potential existing or future receptors within the vicinity of the contamination. The conditions for excluding this exposure pathway and the required distance from receptors is dependent on the policies of the jurisdiction, but would typically include consideration of both the potential distance over which vapours could migrate and the potential for groundwater transport towards downgradient receptors.

The groundwater quality guidelines for the protection of indoor air quality ($GWQG_{IAQ-R}$ for residential buildings and $GWQG_{IAQ-C}$ for commercial buildings) is calculated using the equations presented in Appendix A and model input parameters presented in Appendix B. While residential buildings will result in lower guidelines, guidelines are calculated for both building types to allow for site-specific exclusion of the residential building guidelines when jurisdictional requirements for eliminating this exposure pathway are met. The allowable indoor air concentration originating from groundwater contamination is the tolerable concentration (TC) minus the background indoor air concentration for threshold substances, or the risk-specific concentration (RSC) for non-threshold substances. If only a tolerable daily intake (TDI) or risk-specific dose (RSD) is available, then a toxicity benchmark for inhalation can be calculated as:

$$TC = \frac{TDI \times BW}{IR} \qquad \text{or} \qquad RSC = \frac{RSD \times BW}{IR}$$

where:

TDI	=	tolerable daily intake (mg/kg/d)
RSD	=	risk-specific dose (mg/kg/d)
BW	=	body weight (kg) of the critical receptor (Appendix I)
IR	=	air inhalation rate (m^3/d) of the critical receptor (Appendix I)

It should be noted that there may be considerable uncertainty in a TC or RSC extrapolated from an oral toxicity benchmark, since the target organs and toxicity mechanisms may be different for inhalation exposure than for oral exposure. However, in the absence of inhalation-specific toxicity benchmarks, use of an extrapolated toxicity benchmark is considered to be more appropriate than excluding the pathway for protection of indoor air quality for a volatile organic compound.

PART D

1. Derivation of the Final Groundwater Quality Guideline

1.1 Final Guideline Derivation

The goal of the final recommended groundwater quality guideline ($GWQG_F$) is to protect both ecological and human health. The lowest of the pathway-specific guidelines calculated in Part B and Part C of this protocol is recommended as the $GWQG_F$, subject to restrictions discussed in Section D 1.2 below. A general overview of the entire guidelines derivation process outlining major steps leading to derivation of the final groundwater quality guideline is illustrated in Figure 5.

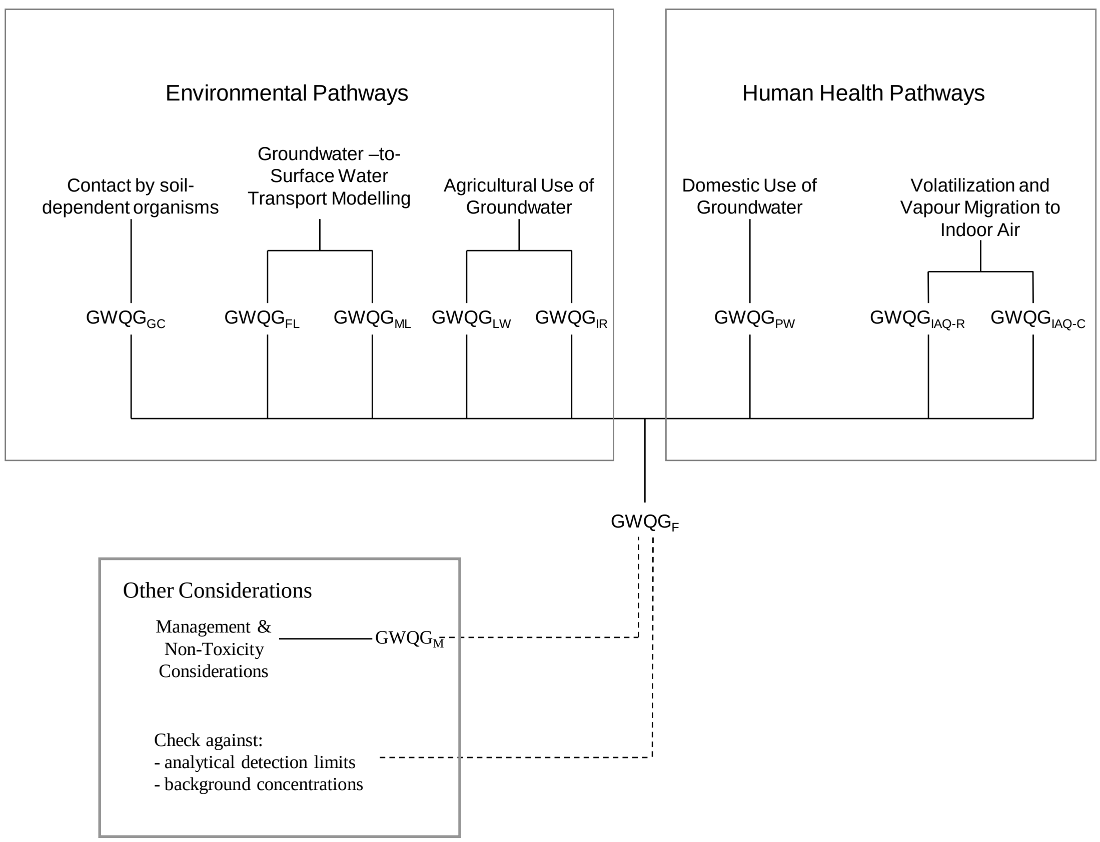

Figure 5: Overview of Steps Leading to Derivation of a Final Groundwater Quality Guideline

The guidelines for the protection of potable water ($GWQG_{PW}$) and protection of aquatic life, freshwater ($GWQG_{FL}$) and marine ($GWQG_{ML}$), are considered to be required exposure pathways; if one or both of these guidelines cannot be established then the $GWQG_F$ is considered to be a provisional guideline.

Development of Canadian groundwater quality guidelines is complex and involves many parameters. While some parameters are known with great precision, most of them are estimates with considerable variability. In consideration of this and other uncertainties in the guideline development process, $GWQG_F$ are rounded to not more than two significant figures for presentation in assessment documents.

In some cases, a pathway-specific guideline exceeding 1,000,000 mg/L (i.e., a concentration exceeding 100% by weight) may be calculated; in this case, the guideline for that exposure pathway is reported as “NA”.

1.2 Considerations Other than Toxicity - Management Limits

Contaminants may have adverse effects in addition to producing toxic responses in human and ecological receptors. These may include aesthetic concerns (e.g., odours), explosive hazards, free-phase liquid formation, or damage to utilities and infrastructure. Additionally, certain exposure pathways may be relevant for a chemical, but be subject to uncertainty or not have well-defined methods for their evaluation (e.g., exposure of workers in excavations or utility trenches).

If there is evidence that a contaminant may cause significant environmental effects beyond toxicity to human and ecological receptors as captured in the exposure pathways detailed in Parts B and C, then this evidence should be evaluated. A groundwater quality guideline for management considerations ($GWQG_M$) is developed to reflect any additional concerns associated with the contaminant. At this time, standard methods for the calculation of management limits have not been established, and each chemical should be evaluated on a case-by-case basis. However, some considerations are listed below.

As a minimum, the solubility limit of a chemical should be considered in the derivation of the $GWQG_M$, due to the potential for chemical concentrations approaching solubility to result in non-aqueous phase liquids (NAPLs) that may act as an ongoing contaminant source. In general, the $GWQG_M$ should not exceed 50% of the chemical’s aqueous solubility limit. This Management Limit is intended as an alert to the potential presence of upstream sources of free phase; this Management Limit is not intended to prevent free phase formation. Professional judgment should be applied for chemicals with relatively low solubility limits which would be present mainly in the adsorbed phase. For high molecular weight chemicals, dissolved concentrations should not exceed 10% of their theoretical solubility limit. In general, this rule should not normally be used to lower guidelines below the limit of practical quantitation, and normally the $GWQG_M$ based on solubility should not be lower than the lowest guideline based on human or environmental effects.

For chemicals where a noticeable odour is likely to occur at a lower concentration than toxicity, it may be appropriate to consider the potential for odours in indoor air. This could be achieved by using the same model and assumptions as for the indoor vapour inhalation exposure pathway

(Appendices A and B), but replacing the TC with the odour threshold of the chemical. The allocation factor should be set to 1 for this calculation.

There may be considerable uncertainty in the development of the $GWQG_M$, and for some concerns associated with contaminants only a qualitative evaluation may be possible. Therefore, professional judgement should be used as to whether the $GWQG_F$ should be adjusted based on the $GWQG_M$ if it is lower than the guidelines for other exposure pathways. If the $GWQG_M$ is higher than guidelines for other pathways, then it may be appropriate to use the $GWQG_M$ as an upper limit on Tier 2 site-specific guidelines.

1.3 Degradation Products

Certain contaminants may potentially degrade into more toxic or more mobile chemicals (e.g., degradation of trichloroethylene to vinyl chloride). Since degradation rates are affected by several site-specific factors, at this time a formal method for adjusting groundwater quality guidelines to reflect degradation into more toxic compounds is not specified. However, where data support doing so, accounting for degradation to more toxic compounds should be considered on a chemical-specific basis. Furthermore, major degradation products should be highlighted in the scientific criteria document and fact sheet to ensure that users are aware of these degradation products and that site assessments take degradation products into consideration, particularly when developing long-term monitoring strategies.

1.4 Evaluation against Background Concentrations and Practical Quantitation Limits

Guidelines should be reasonable, workable and usable. Guidelines are developed by applying scientifically derived information, backed by professional judgement where data gaps occur. Occasionally a calculated guideline may be lower than background concentrations or practical quantitation limits, however.

Where the $GWQG_F$ is less than typical Canadian background concentrations, CCME recommends that the accepted background concentration replace the $GWQG_F$ generated using this protocol. More commonly, the $GWQG_F$ may be higher than the typical Canadian background concentration, but specific locations may have unusually high background concentrations exceeding the $GWQG_F$. In these cases, jurisdictions have the option to set site-specific or regional guidelines that consider the background concentrations.

A candidate $GWQG_F$ should also be checked against the current practical quantitation limit of available analytical methods achievable in Canada (generally 5 times the analytical detection limit). Where the $GWQG_F$ is below the limit of practical quantitation, a footnote should be added to the $GWQG_F$ stating, “laboratories may not be able to reliably measure concentrations of this magnitude.” The $GWQG_F$ should not be adjusted based on the practical quantitation limit, however, although individual jurisdictions may incorporate practical quantitation limits in their implementation of the guideline.

Because guidelines are based primarily on biological effects and background exposures are, wherever possible, incorporated into the procedures, it is anticipated that very few candidate

$GWQG_F$ will require adjustment. Where any of the evaluation procedures described above does result in modification of a candidate $GWQG_F$, this condition will be noted in the assessment document for the substance.

1.5 Presentation of Groundwater Quality Guidelines

The groundwater quality guidelines will be presented in tabular format, showing the guidelines developed for each receptor-exposure pathway and the final groundwater quality guideline. An example is shown below (separate tables will be prepared for coarse and fine-grained soils, and for non-threshold substances for both 1 x 10^{-5} and 1 x 10^{-6} incremental risk levels):

Table 2. Example of Groundwater Quality Guideline Presentation

	Soil Type	
	Coarse	Fine
Guideline ($GWQG_F$)	##	##
Groundwater Contact ($GWQG_{GC}$) by soil-dependent organisms	##	##
Protection of freshwater life ($GWQG_{FL}$)	##	##
Protection of marine life ($GWQG_{ML}$)	##	##
Protection of livestock watering ($GWQG_{LW}$)	##	##
Protection of irrigation water ($GWQG_{IR}$)	##	##
Protection of potable water ($GWQG_{PW}$)	##	##
Protection of indoor air quality – residential ($GWQG_{IAQ-R}$)	##	##
Protection of indoor air quality – commercial ($GWQG_{IAQ-C}$)	##	##
Management considerations ($GWQG_M$)	##	##

1.6 Scientific Supporting Documents

Scientific supporting documents and fact sheets are described in Section D 1.6 of the soil protocol (CCME, 2006). For substances with an existing soil quality guideline, the groundwater quality guideline should draw on (or update) the existing scientific supporting document; the document should be updated to reflect the groundwater quality guideline or an addendum should be produced describing the derivation of the groundwater quality guideline. If there is no existing soil quality guideline, then a new scientific supporting document will be prepared; it is anticipated that in these cases the groundwater quality guidelines would be developed in parallel with soil quality guidelines.

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APPENDIX A - SUMMARY OF MODELS AND EQUATIONS USED IN GROUNDWATER QUALITY GUIDELINE DEVELOPMENT

ENVIRONMENTAL EXPOSURE PATHWAYS

Groundwater Quality Guidelines for Plant and Invertebrate Groundwater Contact

Groundwater quality guidelines for this exposure pathway are calculated using the following equations. Details of the derivation of these equations are provided in Section B 4.2.

$$GWQG_{GC} = \frac{SQG_{SC}}{DF1} \qquad \text{(Equation A-1)}$$

$$DF1 = K_{oc} \times f_{oc} + \frac{(\theta_w + H' \times \theta_a)}{\rho_b} \qquad \text{(Equation A-2)}$$

Where:

$GWQG_{GC}$	=	groundwater quality guideline for groundwater contact by soil-dependent organisms (plant and invertebrate) (mg/L)
SQG_{SC}	=	soil quality guideline for soil contact by soil-dependent organisms (plant and invertebrate) for agricultural land use (mg/kg)
DF1	=	dilution factor 1 (L/kg)
K_{oc}	=	organic carbon-water partition coefficient (L/kg)
f_{oc}	=	fraction organic carbon (g/g)
θ_w	=	water filled porosity in the vadose zone (dimensionless)
H'	=	dimensionless Henry's Law constant (dimensionless)
θ_a	=	air filled porosity in the vadose zone (dimensionless)
ρ_b	=	bulk density of soil in the vadose zone (dry basis) (g/cm^3)

Note that the SQG_{SC} for agricultural land is used to develop Tier 1 $GWQG_{GC}$ values for all land uses. See Appendix A of the soil protocol for calculation of K_d for dissociating organic compounds.

Groundwater Quality Guidelines for the Protection of Aquatic Life

Groundwater quality guidelines for this exposure pathway are calculated based on the time dependent model for centreline plume concentrations from Domenico (1987). The equation has been modified to reflect the conservative assumption that there is no dispersion in the vertical (z) direction. The model is consistent with the corresponding CCME model (saturated zone transport portion) for soil quality guidelines (assuming that the arbitrary value of time, t, in the soil guidelines model is sufficiently long to ensure steady state) and is as follows.

$$GWQG_{FL/ML} = \frac{4 \times SWQG}{\exp(A) \times erfc(B) \times [erf(C) - erf(D)]} \quad \text{(Equation A-3)}$$

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

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

$$C = \frac{y + Y/2}{2(\partial_y x)^{1/2}} \qquad D = \frac{y - Y/2}{2(\partial_y x)^{1/2}}$$

Where:

$GWQG_{FL\ or\ ML}$	=	groundwater quality guideline for the protection of aquatic life (freshwater or marine) (mg/L)
SWQG	=	surface water quality guideline for the protection of aquatic life (freshwater or marine) (mg/L) (i.e., Canadian Water Quality Guideline for the Protection of Aquatic Life, if available)
A, B, C, D	=	intermediate values in the calculation
x	=	distance from source to receptor (m)
∂_x	=	longitudinal dispersivity = 0.1x (m)
∂_y	=	lateral dispersivity = $0.1\partial_x$ (m)
L_s	=	decay constant (y^{-1}) in saturated zone: $L_s = \frac{0.693}{t_{1/2S}}(e^{-0.07d})$
d	=	depth from surface to groundwater surface (m)
$t_{1/2s}$	=	biodegradation half-life in saturated zone (y)
v	=	velocity of contaminant (m/y): $v = \frac{K_H i}{n_e R_f}$
K_H	=	hydraulic conductivity in the saturated zone (m/y)
i	=	lateral hydraulic gradient (unitless)
n	=	total porosity of saturated zone = 1 - ρ_b/2.65 (unitless)
n_e	=	effective porosity of saturated zone (unitless); generally assumed to be the same as total soil porosity (n)
t	=	time at which guideline is evaluated (years, see Appendix B for discussion)
y	=	Cartesian coordinate relating source to receptor (m); y assumed to be 0
Y	=	contaminant source width (m) perpendicular to groundwater flow
R_f	=	retardation factor (unitless)

$$R_f = 1 + \frac{\rho_b}{n} K_d$$

ρ_b = soil bulk density in saturated zone (g/cm^3)
K_d = distribution coefficient (cm^3/g) – see Appendix A of the soil protocol for dissociating organic compounds, for non-dissociating organic compounds use:

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

K_{oc} = organic carbon partitioning coefficient (L/kg)
f_{oc} = organic carbon fraction of soil (g/g)

Groundwater Quality Guidelines for the Protection of Livestock Watering and Irrigation Water

Groundwater quality guidelines for these exposure pathways are adopted directly from the Canadian Water Quality Guidelines for Agricultural Water Uses (CCME, 1999).

HUMAN HEALTH EXPOSURE PATHWAYS

Groundwater Quality Guidelines for the Protection of Potable Water

Groundwater quality guidelines for this exposure pathway are adopted directly from the Guidelines for Canadian Drinking Water Quality or from Provisional Source Guidance Values for Groundwater developed by Health Canada.

Groundwater Quality Guidelines for the Protection of Indoor Air Quality

Threshold chemicals:

$$GWQG_{IAQ} = \frac{(TC - C_a) \times AF \times DF_i \times Adj.F}{H' \times ET \times 10^3 \, L/m^3} + BGC \qquad \text{(Equation A-4)}$$

Non-threshold chemicals:

$$GWQG_{IAQ} = \frac{RsC \times DF_i \times Adj.F}{H' \times ET \times 10^3 \, L/m^3} + BGC \qquad \text{(Equation A-5)}$$

Where:
$GWQG_{IAQ}$ = groundwater quality guideline for the protection of indoor air quality (mg/L)
TC = tolerable concentration or reference concentration (mg/m^3)
RSC = risk-specific concentration (mg/m^3)
C_a = background indoor/outdoor air concentration (mg/m^3)

AF = allocation factor (unitless)
H' = unitless Henry's Law Constant = H/RT
H = Henry's Law Constant (atm-m^3/mol)
R = gas constant (8.2 x 10^{-5} atm-m^3/mol-K)
T = annual average groundwater temperature (K)(288 K = 15°C)
DF_i = dilution factor from soil gas to indoor air (unitless): ***see derivation below***
Adj.F = adjustment factor (unitless) = 10 at Tier 1 for petroleum hydrocarbons (F1, F2, BTEX) and short chain alkanes: = 1 for non-petroleum hydrocarbons.
ET = exposure term (unitless)
BGC = background groundwater concentration (mg/L)

Calculation of DF for indoor infiltration pathway:

$$DF_i = \frac{1}{\alpha}$$ (Equation A-6)

DF_i = dilution factor from soil gas concentration to indoor air concentration (unitless)
α = attenuation coefficient
= (contaminant vapour concentration in the building)/(vapour concentration at the contaminant source)

$$\alpha = \frac{\left(\frac{D_T^{eff} A_B}{Q_B L_T}\right) \exp\left(\frac{Q_{soil} L_{crack}}{D^{crack} A_{crack}}\right)}{\exp\left(\frac{Q_{soil} L_{crack}}{D^{crack} A_{crack}}\right) + \left(\frac{D_T^{eff} A_B}{Q_B L_T}\right) + \left(\frac{D_T^{eff} A_B}{Q_{soil} L_T}\right)\left[\exp\left(\frac{Q_{soil} L_{crack}}{D^{crack} A_{crack}}\right) - 1\right]}$$

D_T^{eff} = effective porous media diffusion coefficient (cm^2/s) – see below
A_B = building area – floor and subgrade walls (cm^2)
Q_B = building ventilation rate (cm^3/s) – see below
L_T = distance from contaminant source to foundation (cm)
Q_{soil} = volumetric flow rate of soil gas into the building (cm^3/s) (see below)
L_{crack} = thickness of the foundation (cm)
D_{crack} = effective diffusion coefficient through the crack (cm^2/s)
A_{crack} = area of cracks through which contaminant vapours enter the building (cm^2)

Calculation of effective porous media diffusion coefficient in the unsaturated zone (D_T^{eff}):

$$D_T^{eff} = D_a \cdot \left(\frac{\theta_a^{10/3}}{n^2}\right) + \left(\frac{D^{water}}{H'}\right) \cdot \left(\frac{\theta_w^{10/3}}{n^2}\right)$$ (Equation A-8)

D_T^{eff}	=	overall effective porous media diffusion coefficient based on vapour-phase concentrations for the region between the source and foundation (cm^2/s)
D_a	=	pure component molecular diffusivities in air (cm^2/s)
D^w	=	pure component molecular diffusivity in water (cm^2/s)
H'	=	dimensionless Henry's Law constant (unitless) at soil temperature (e.g. 15C)
θ_w	=	moisture-filled porosity (unitless)
θ_a	=	vapour-filled porosity (unitless)
n	=	total soil porosity (unitless)

Calculation of effective diffusion coefficient through the crack (D_{crack}):

$$D_{crack} \approx D_a \cdot \left(\frac{\theta_a^{10/3}}{n^2} \right)$$

D_{crack}	=	effective diffusion coefficient through the crack (cm^2/s) (assumes soil in cracks is dry and coarse texture)
D_a	=	pure component molecular diffusivities in air (cm^2/s)
θ_a	=	vapour-filled porosity (unitless) – assumed to be equal to total soil porosity, *n*
n	=	total soil porosity (unitless)

For the effective diffusion coefficient through the crack (D_{crack}), it is assumed that a coarse, granular material is used as the base for the floor and footings. Therefore, it is assumed that the cracks are filled with coarse soil, even if the native soil is fine/medium textured regardless of the surrounding soil texture.

Calculation of building ventilation rate (Q_B):

$$Q_B = L_B W_B H_B (ACH) / (3600\ s/h) \quad \text{(Equation A-10)}$$

Q_B	=	building ventilation rate (cm^3/s)
L_B	=	building length (cm)
W_B	=	building width (cm)
H_B	=	building height, including basement (cm)
ACH	=	air exchanges per hour (h^{-1})

Calculation of soil gas flow rate (Q_{soil})

Q_{soil} is no longer calculated from soil/building properties (i.e., perimeter crack model), but rather is a fixed value based on soil texture and land use (see Appendix B for details).

APPENDIX B - DEFAULT PARAMETERS FOR GUIDELINE DEVELOPMENT

This appendix presents the default values used to calculate groundwater quality guidelines, along with relevant background information. These values may be updated from time to time; it should be noted that existing groundwater quality guidelines are not normally revised when these default values are changed.

Table B.1 Human Receptor Characteristics[a]

Parameter	Symbol	Infant (0 – 6 mo)	Toddler (7 mo - 4 y)	Child (5 – 11 y)	Teen (12 – 19 y)	Adult (20+ y)
Body Weight (kg)	BW	8.2	16.5	32.9	59.7	70.7
Air Inhalation Rate (m^3/d)	IR	2.2	8.3	14.5	15.6	16.6
Water Ingestion Rate (L/d)	WIR	0.3	0.6	0.8	1.0	1.5

a – all values from Health Canada, 2004

Body Weight
Average body weights were recommended by Health Canada (2004), based on surveys conducted in 1981 for adults (CFLRI, 1981) and 1970-1972 for children (EHD, 1992). Weight increases were observed in the Canadian population over the period from 1970 through 1988 (Richardson, 1997).

Inhalation Rate
The inhalation rates were generated using data on time-activity information for the Canadian population combined with ventilation rates reported for different activity levels (Richardson, 1997, and updated information for infant, toddler, teen, and adult in Allan *et al*., 2008).

Water Ingestion Rate
Water ingestion rates are based on a study of Canadian tap water consumption conducted during 1977-1978 (NHW, 1981), involving questionnaires and individual water consumption diaries.

Table B.2 Soil and Hydrogeological Parameters

Parameter	Symbol	Soil Type Coarse-grained	Fine-grained
Saturated Hydraulic Conductivity (m/y)	K_H	320	32
Hydraulic Gradient	i	0.028	0.028
Organic Carbon Fraction (g/g)	foc	0.005	0.005
Soil Bulk Density (g/cm^3)	ρ_b	1.7	1.4
Total Soil Porosity	n	0.36	0.47
Vapour-Filled Porosity ($GWQG_{GC}$)	θ_a	0.241	0.302
Moisture-Filled Porosity ($GWQG_{GC}$)	θ_w	0.119	0.168
Vapour-Filled Porosity ($GWQG_{IAQ}$)	θ_a	0.31	0.302
Moisture-Filled Porosity ($GWQG_{IAQ}$)	θ_w	0.05	0.168
Soil Gas Flow Rate (cm^3/s)[a]	Q_{soil}	167	16.7

a – based on a flow rate of 10 L/min for coarse soils and 1 L/min for fine soils

Saturated Hydraulic Conductivity

The default values for hydraulic conductivity were chosen to reflect typical aquifers encountered in Canada. The coarse-grained soil value (320 m/y) is representative of silty sand (Freeze and Cherry, 1979), and was selected because low values are more conservative (i.e., result in lower guidelines) for exposure pathways where there is no offset distance between the contamination and the groundwater receptor. This value may not be conservative for exposure pathways involving saturated zone transport; however, higher saturated hydraulic conductivities would likely be at least partially offset by associated lower hydraulic gradients. A hydraulic conductivity of 3.2 m/y is representative of silt (Freeze and Cherry, 1979); however, for fine-grained soil a value of 32 m/y is used to reflect the upper end of the range of fine-grained soils.

Hydraulic Gradient

The hydraulic gradient is a dimensionless quantity describing the steepness of the water potential gradient. In unconfined aquifers, it is roughly equivalent to the gradient of the water table. A hydraulic gradient of 0.028 is recommended as a default value (CCME, 2006); hydraulic gradient is inversely correlated with the saturated hydraulic conductivity. It should be noted that where the hydraulic gradient of a site is known to differ significantly from 0.028, calculation of Tier 2 guideline values should use the site-specific hydraulic gradient in the saturated zone transport calculations for all relevant groundwater exposure pathways.

Organic Carbon Fraction

The default organic carbon fractions for coarse and fine-grained soils are based on a review of the organic carbon contents of various Canadian subsoils undertaken in support of the Canada-wide Standard for Petroleum Hydrocarbons in Soil (PHC CWS) (CCME, 2008b).

Soil Bulk Density and Moisture Content

The default soil bulk densities and moisture contents were chosen to be representative of typical sand (coarse-grained) and clay (fine-grained) soils. The moisture-filled porosity for coarse-grained soils was modified to be consistent with Health Canada recommendations for input values for the Johnson and Ettinger model (HC 2010e), and default values in the CCME soil vapour protocol (CCME 2014).

Porosity
The total soil porosity is calculated from the soil bulk density, assuming a particle density of 2.65 g/cm^3. The moisture-filled porosity is calculated as the soil bulk density multiplied by the moisture content (assuming a water density of 1 g/cm^3). The vapour-filled porosity is obtained by subtracting the moisture-filled porosity from the total porosity.

Minimum Soil Gas Flow Rate into Buildings
The CCME (2006) soil protocol calculated soil gas flow rate based on soil vapour permeability and pressure differentials; due to the difficulties associated with reliably measuring these parameters and more recent research into this migration pathway, the soil gas flow rate is now defined directly. See Appendix C of A Protocol for the Derivation of Soil Vapour Quality Guidelines For Protection of Human Exposures Via Inhalation of Vapours (CCME, 2014) for more details.

Table B.3 Site Characteristics and Other Parameters

Parameter	**SYMBOL**	**VALUE**
Contaminant Source Width (m)	Y	10
Distance to Surface Water (m)	x	10
Distance to Potable Water User (m)	x	0
Distance to Agricultural Water User (m)	x	0
Distance from Groundwater to Building Slab (cm)	L_T	100
Time at which Groundwater Model is Evaluated (years)	t	≥100

Source Width
Dimensions of the contaminated area are assumed based on typical contaminated sites in Canada. Width is defined in the direction perpendicular to groundwater flow.

Distance to Surface Water
It is assumed for purposes of generic guideline development that a surface water body could be located 10 m from the remediated groundwater. An offset distance is considered possible for this exposure pathway (protection of aquatic life), since the locations of surface water bodies are normally relatively unchanging.

Distance to Potable and Agricultural Water Users
Potable water and agricultural water users are assumed to be located within the remediated groundwater (i.e., zero distance between contaminant and extraction point). Potable water and agricultural water users may also be at the downgradient edge of the remediated groundwater. Inclusion of an offset distance for these exposure pathways on a generic basis may lead to inappropriate or unmanageable water use restrictions; however, offset distances may be incorporated on a site-specific basis where appropriate.

Distance from Groundwater to Building Slab
A minimum of 100 cm separation distance between the capillary fringe and building foundation slab is assumed to be present.

Time at which Groundwater Model is Evaluated
In most cases, 100 years will be a sufficiently long time to ensure that the guidelines calculated reflect steady state. However, a test should always be undertaken to ensure that the calculated guideline represents steady state by substituting a larger value of t, and seeing if the guideline value changes. Particular care should be taken in the case where the assumed degradation rate is very low or zero and/or the Koc of the chemical is high. Some jurisdictions may choose to put an upper bound on the maximum length of time considered.

Depth to Groundwater
CCME's generic conceptual site model assumes that the depth to groundwater is 3 m.

Table B.4 Building Parameters

Parameter	Symbol	Residential	Commercial
Building Length (cm)	L_B	1225	2000
Building Width (cm)	W_B	1225	1500
Building Area (cm^2)	A_B	$2.7x10^6$	$3.0x10^6$
Building Height (cm)[a]	H_B	360	300
Thickness of Building Foundation (cm)	L_{crack}	11.25	11.25
Area of Crack (cm^2)	A_{crack}	994.5	1846
Air Exchanges per Hour (1/h)	ACH	0.5	0.9

a – including basement

Building parameters have been adapted from CCME (2008b), and were originally based on a review of typical building characteristics and building codes.

The slab-on-grade residential building is typically more sensitive to default site parameters than the residential building with a basement due to higher advective flow. Nonetheless, it is recommended that groundwater quality guidelines for the protection of indoor air quality be calculated for both scenarios for residential land uses to ensure that the most sensitive exposure route is considered. For commercial land uses, only slab-on-grade construction will be considered. Parameters for buildings both with and without basements are provided in Table B.4.

Required Chemical Properties

- Tolerable Daily Intake and/or Risk-Specific Dose
- Tolerable Concentration and/or Risk-Specific Concentration (volatile chemicals)
- Estimated Daily Intake (threshold chemicals)
- Background Groundwater Concentration (assumed to be 0 if no data indicate otherwise)
- Background Air Concentration (volatile threshold chemicals)
- Henry's Law Constant (volatile chemicals)
- Diffusion Coefficient in Air (volatile chemicals)

- Half-Life in the Saturated Zone (soluble chemicals)
- Water Solubility (soluble chemicals)
- Organic carbon-water partition coefficient

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