Review of Environmental Radioactivity in Canada

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ABSTRACT

Title: **Review of Environmental Radioactivity in Canada**
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Abstract
The objective was to review and summarize background concentrations of radionuclides in surface water and soil across Canada. Three types of radionuclides were considered. The first radionuclides were primordial, including parents and progeny of ^{235}U, ^{238}U and ^{232}Th, ^{40}K and ^{97}Rb. The second were rare but naturally occurring radionuclides of special interest, including ^{3}H, ^{14}C, ^{36}Cl and ^{129}I. The third were fallout radionuclides with emphasis on ^{3}H, ^{14}C, ^{137}Cs and ^{90}Sr. Data were obtained specifically for Canadian sites, but included data from international sources as needed. Contaminated sites were avoided, but associated control-site data were evaluated. The temporal domain was present-day, but with attention to any potentially important trends, notably time since atmospheric nuclear bomb testing. In addition to the background radionuclide concentrations, Environment Increments were also identified that are one geometric standard deviation above the background geometric mean value.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1 OBJECTIVE

The objective of the project was to review and summarize background concentrations of radionuclides in surface water and soil across Canada. Three suites of radionuclides were considered. The first were primordial radionuclides, including parents and progeny of ^{235}U, ^{238}U, ^{232}Th, ^{40}K and ^{97}Rb. The second were rare but naturally produced radionuclides of special interest for radioactive waste management, ^{3}H, ^{14}C, ^{36}Cl and ^{129}I. The third were fallout radionuclides with emphasis on ^{137}Cs and ^{90}Sr.

The spatial domain was Canada, with emphasis on the nuclear provinces (Saskatchewan, Ontario, Quebec and New Brunswick), but drawing data from international sources as needed. Contaminated sites were avoided, but associated control-site data were evaluated. The temporal domain was present-day, but with attention to any potentially important trends such as time since Chernobyl, time since atmospheric nuclear bomb testing and time related to changes in fuel reprocessing locations and intensities.

1.2 BACKGROUND VERSUS ANTHROPOGENIC RADIONUCLIDES

The general objective is to identify background concentrations. In practice, this means consideration of the likely sources of the radionuclide, and taking this into account in selection of data to compile. For example, radionuclides from present and past nuclear facilities have affected concentrations, locally in some cases and globally in others. Local contamination is clearly not background and so such data were avoided in this study. Global contamination has become the *de facto* background, but may result in concentrations that are above the concentration range present when organisms evolved. For radionuclides where global contamination is present, both the present background concentrations and the pre-anthropogenic background concentrations have value, and both are summarised here where possible.

The atmospheric nuclear bomb test fallout[1] radionuclides, ^{137}Cs and ^{90}Sr, are the prime example of global contamination. These were distributed and deposited globally, with the highest levels of deposition in the mid-latitudes of the Northern Hemisphere. Each bomb test produced a cloud of fallout and deposition at any one location was dependent on dispersion of the cloud and the occurrence of rainfall when the cloud passed, among other variables. However, over the several decades when fallout was produced, the distribution of these radionuclides became fairly uniform at least on a regional scale. The Chernobyl accident produced a similar cloud, but the often-noted heterogeneity in deposition of radionuclides from the Chernobyl cloud is because it was a single event. In terms of total amounts of radionuclides, Chernobyl was minor relative to bomb-test fallout.

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[1] Hereafter referred to as 'fallout'

Carbon-14 is different from most other radionuclides because burning of fossil fuels has actually diluted global cosmogenic[2] ^{14}C with old, low-^{14}C-carbon from the fossil fuel, such that the current global specific activity[3] of ^{14}C is less than the natural background level. This dilution of ^{14}C has lowered doses: dose from ^{14}C is proportional to specific activity because C is a major component of all biological compounds and tissues[4].

Another important global trend occurs for ^{129}I. Global concentrations of ^{129}I are rising as more fuel reprocessing and fuel waste packaging is done (Aldahan et al. 2006, 2007b). Although the contamination arises from relatively few point sources, the major ones being La Hague in France and Sellafield in the UK, their impact can be detected globally (Moran et al. 2002). There are related spatial trends. Concentrations of ^{129}I in Europe and Scandinavia are clearly much higher than typical of the rest of the world. More relevant to Canada, there continue to be low but elevated concentrations of ^{129}I within a few hundred kilometres of West Valley NY, even though relatively little fuel reprocessing was done there (Rao and Fehn 1997, Moran et al. 2002). There is also a distinct but unidentified source in the north eastern US (Moran et al. 2002), which result in a very small signature in Canada.

More important to the present project was the consideration of data from the surrounds of nuclear facilities. The pre-operational sampling and monitoring programs associated with various types of mines, uranium processing facilities and research and power reactor sites all generate data on environmental concentrations. By definition, data from impacted areas near these facilities were not relevant to the present study. The more difficult question was about the control-site data from these facilities. Generally, it was assumed that if the facility operator defined a sampling site as a control site, which was presumably done to meet regulatory needs and inspection, then it was considered uncontaminated and representative of the region for this project.

1.3   NATURAL SOURCES – PRIMORDIAL, COSMOGENIC AND GEOGENIC

The primordial radionuclides, including parents and progeny of ^{235}U, ^{238}U, ^{232}Th, ^{40}K and ^{97}Rb, are the simplest to assign to source. Their parents were present since from the formation of Earth, and although they are not distributed uniformly in all environmental media, they can be assumed to be present in almost all soils and in water that contacts soils and rocks. In contrast, cosmogenic and geogenic radionuclides are constantly produced by natural processes.

Cosmogenic radionuclides result from a range of nuclear reactions initiated by cosmic radiation. Various forms of cosmic radiation impinge on target nuclides in the atmosphere or in the Earth's crust and some of these interactions produce new 'cosmogenic' nuclides. The intensity of production depends on the properties of the cosmic radiation, the density of the target nuclides, the shielding by air, water, snow, soil and rocks as well as latitudinal and other variations in the Earth's magnetic field. The processes are very complicated, and reviews such as Gosse and

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[2] Cosmogenic refers to products of the interaction of cosmic rays or particles with atoms on Earth, and these reactions may occur in the atmosphere (atmospheric cosmogenic) or in rocks and soils (terrestrial cosmogenic)

[3] Specific activity is the decay rate of a radionuclide relative to the corresponding mass of the same element, for example Bq ^{14}C per g C.

[4] The concept is that the organism contains a fixed amount of C, so if the specific activity is lower then the body content of ^{14}C is lower and therefore the dose from ^{14}C to the individual is lower.

Phillips (2001) and Lal (1987) should be consulted. For this report, cosmogenic ^{3}H, ^{14}C, ^{36}Cl and ^{129}I are of most interest.

Another source is geogenic or natural nucleogenic, where neutrons and alpha particles from decay of primordial radionuclides in rocks interact with various targets to produce geogenic nuclides. For example, ^{14}C can be produced in rocks by the interaction of radiogenic neutrons on ^{14}Ni and ^{17}O, and by radiogenic alpha particles on ^{11}B (Gosse and Phillips 2001). In addition, because there is a low level of nuclear fission in U-bearing rocks, spontaneous natural fission releases otherwise rare fission products such as ^{129}I.

To further the example of ^{14}C, most of the cosmogenic ^{14}C is produced in the atmosphere by neutron absorption by nitrogen, but there is 'terrestrial' cosmogenic production in quartz and limestone minerals and the geogenic production described above. The atmospheric cosmogenic ^{14}C is readily soluble, biologically available once deposited to Earth, and therefore very relevant to the background levels considered in this report. In contrast, the terrestrial cosmogenic ^{14}C produced in rocks and the geogenic ^{14}C (also produced in rocks) is generally not easily released from the rock matrices. Thus, although terrestrial cosmogenic and geogenic processes contribute to background ^{14}C per se, this ^{14}C does not have an immediate biological role.

For many of the terrestrial cosmogenic radionuclides, there has been considerable recent research to use these to date geomorphic processes: this was the topic of the review by Gosse and Phillips (2001), for example. Because the production rate in rocks decreases markedly with depth, the presence of the terrestrial cosmogenic radionuclides in surface rocks allows an estimate of how long they have been exposed, which is useful to date events such as glacial retreat and volcanism. However, this body of research specifically attempts to exclude atmospheric cosmogenic radionuclide production, which is arguably more important for background environmental radioactivity.

1.4   VARIABILITY AND ENVIRONMENTAL INCREMENTS

Background concentrations are clearly not constant in space or time, and in many respects the variation in background concentrations is at least as important as are the medians or means. Thus in this report, emphasis is given to measures of variability and to the corresponding data frequency distributions.

Another use of the measures of variability is that of Environmental Increments (EI). Amiro (1992, 1993) and later Solberg-Johansen et al. (1997) proposed a scheme to compile background concentration data for soil and water from a variety of sources and then generate EI values. These EI values were intended to be the increment in concentration above background that was well assured to not have an impact on ecological attributes or human health. Values of EI have been called an estimate of the 'contaminant carrying capacity' of the biosphere. In many cases, these EI values were based on the statistical dispersion of measured or estimated concentrations rather than on demonstrated effect concentrations, so the scheme was quite dependent on good background concentration data. Environmental Increment values based on statistical dispersion are computed in this report and serve to characterize the variation in background concentrations.

There are many sources of variation, some systematic and some random. There is imprecision and inaccuracy related to the radiochemical analysis method, which approaches 100% as concentrations approach the detection or quantification limit. For many radionuclides, background concentrations are near or below the detection limits, so this source of variation can become important. There is variation because of sampling: the samples may not represent the media sampled, usually because of small-scale spatial variation. Finally, there are multiple levels of spatial variation, perhaps best reflected in the semi-variograms used in spatial analyses and fractal analysis.

In a semi-variogram, the variation among samples is plotted as a function of the distance between sampling positions, and the result tends to asymptotic. However, there can be multiple asymptotes. With soils as an example, variation may reach an apparent asymptote and be quite stable within distances defined by the specific soil type and landscape. This may change as soils with different underlying geological parent materials are included, so that another apparent asymptote is reached. Ultimately, there is an asymptote that reflects samples from all soils on Earth. A similar situation occurs for surface waters. Clearly, this leads to a key question about the spatial scale needed to characterize variability.

To illustrate the effect of spatial scale, if one were to focus the EI concept on a small spatial scale, there would be low spatial variability and therefore the apparent contaminant carrying capacity would be negligible. For example, if the spatial scale was one well-mixed lake, there would be almost no spatial or sampling variation, and the EI would be based largely on analytical variation and would be very restrictive. Conversely, if the EI was focussed on a large spatial scale, such as a continent, then there would be substantial variability and therefore a large apparent contaminant carrying capacity.

One conceptual resolution to the problem is to consider the population range of the organisms to be protected. In general, most organisms, including humans, have population ranges of hundreds to thousands of kilometres, so their evolution was subject to the variations in background concentrations over at least regional to continental scales. These scales would seem a reasonable working hypothesis for the spatial scale needed to characterize variation in background concentrations in the context of impact assessment. However, the appropriate spatial domain could be much smaller, especially for rare or endangered species and if they were indeed impacted by the nuclide of concern.

1.5   SOURCES OF REGIONAL VARIABILITY

Spatial distributions for radionuclide concentrations has been most thoroughly investigated for ^{238}U and ^{232}Th in soils and outcrops, because ^{238}U is economically important and because progeny of both can be detected by mobile gamma spectrometers that can yield detailed spatial resolution. There has also been considerable investigation of spatial variation in ^{137}Cs, again because it is easily detected by mobile gamma spectrometers, but also because most of the ^{137}Cs came as a pulse in time[5], and present day spatial variation reflects lateral movement since the pulse. Along with these, spatial variation of ^{40}K is often reported, because it is obtained by the same methods at the same time. However, ^{40}K has such a long half-life that it has a nearly constant specific activity, and stable K is ubiquitous.

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[5] Almost all the ^{137}Cs in soils and surface waters came from fallout, which affected all soils and surface waters and which peaked in 1963. There are more localized and lesser sources, including deposition from the Chernobyl accident.

There are detailed maps of U and Th[6] distributions (http://gdr.nrcan.gc.ca/gamma/comp_e.php, accessed March 2011, some of which are in Appendix B). These show ranges of at least an order of magnitude over distances of ten to hundreds of kilometres. The U and Th activity levels shown on the maps are dependent on surface material, especially outcrop versus soil.

All the radionuclides in this study could be considered ubiquitous. Those that are cosmogenic (^{3}H, ^{14}C, ^{36}Cl and ^{129}I) or from fallout (^{3}H, ^{14}C, ^{36}Cl, ^{90}Sr , ^{129}I and ^{137}Cs) were subject to mixing in the atmosphere followed by dry and wet deposition. Although this generally resulted in uniformity, they have distinct latitudinal trends in concentrations as a result of the magnetic-field effects on cosmic rays and global circulation effects. Regional water balance also has an effect: arid regions have retained most of the deposited radioactivity whereas leaching and runoff have often decreased concentrations in more humid regions. These atmospheric source radionuclides also have a distinct depth distribution, with higher concentrations near the surface and lower concentrations with depth. As an example, ^{3}H as tritiated water has often penetrated to tens of metres in groundwater recharge areas, but is depleted at deeper depths because of radioactive decay. The depth gradient is steeper for ^{137}Cs, which in many locations is still within a few centimetres of the surface even 45 years after the peak deposition of fallout.

There is some local lateral redistribution of the atmospheric-source radionuclides. Cesium-137 has not migrated to deeper soils, but has migrated laterally in the landscape as a result of erosion. This effect is relatively subtle and is more related to total ^{137}Cs in a soil or sediment profile than to concentrations per se, because the erosion is a displacement of a mass of material along with the ^{137}Cs. There are similar subtle lateral gradients for ^{14}C, resulting from biological isotopic discrimination. Landi et al. (2003) showed a small effect of climatic zone across Saskatchewan on ^{13}C (and by inference ^{14}C) content of soil organic matter, because there are fewer C4 plants in northern boreal forests compared to southern grasslands[7].

As already inferred, the primordial radionuclides vary spatially because of differences in mineral composition of the surface materials. This can result in relatively sharp boundaries in levels of radioactivity between adjacent areas of different lithology. At the upper concentrations, there are rare sites of exposed mineralization, in the order of percentage level concentrations of U, which may be considered minable assets. There are other processes that can concentrate U to quite high concentrations near the surface, by combined lateral water flow regimes, sorptive materials and changes in oxidation/reduction (redox) potential. These are sometimes called 'roll fronts' (e.g. the site investigated by CBCL (1985) in Newfoundland), and these are also rare.

In counterbalance to the linkage between radioactivity and lithological characteristic of the long-lived primordial radionuclides, much of the radiological dose to humans arises from decay products of radon (^{222}Rn) (Walsh 1970). Radon can be emitted to the atmosphere as a gas, with the result that ^{222}Rn, ^{210}Bi, ^{210}Po and ^{210}Pb are subject to some spatial homogenization by atmospheric dispersion despite the fixed and sometimes inhomogeneous distribution of ^{226}Ra and its predecessor radionuclides in soils and rocks.

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[6] These are reported as eU and eTh, indicating 'effective' ^{238}U and ^{232}Th concentrations. This is because only progeny of these radionuclides are actually detected, and the eU and eTh concentrations are computed assuming secular equilibrium (and with corrections related to detector efficiencies and measurement geometry).

[7] C4 plants, which include many grass species, have a different biochemical pathway for photosynthesis than other plants and C4 plants tend to discriminate C isotopes less than do other plants.

1.6 FREQUENCY DISTRIBUTIONS

An important aspect of presenting statistical dispersion is consideration of the frequency distribution appropriate for the data. Frequency distributions can be described with many different functions, but two are especially common for environmental variables: normal and lognormal. It is appropriate to test for the best fit function for each data set, but there are some overall, *a priori* considerations.

In general, data are normally distributed for parameters related to constrained systems. For example, parameters that are in proportion to the size of an organism, such as weight, feed intake and breathing rate, tend to be normally distributed. The Central Limit Theorem provides some guidance: it indicates that parameters that are the result of additive processes will more likely be normally distributed. One could envision the weight of an animal as the sum of the weight of its parts. For concentration data, elements that are widely and uniformly distributed may be normally distributed: concentration of potassium (K) in soils is an example.

Other than for widely distributed nuclides, concentration data tend to be lognormally distributed. Another term for this is 'skewed', implying many more low values than high values in the data set. In part, this also follows from the Central Limit Theorem. If added quantities tend to lead to normal distributions, then it follows that multiplicative (or divisive) quantities will tend to lead to lognormal distributions. This is because the sum of log values is equivalent to the multiplication of their linear counterparts, and conversely the difference of log values is equivalent to the division of their linear counterparts. Concentrations of elements are the amount of element divided by the amount of media, and so lognormal may be the best *a priori* assumption. There is a spatial argument too, especially easily envisioned for elements that mainly come from discrete sources. If a fixed amount of an element is released from a discrete source (by man or by natural processes), it will be diluted as it disperses, and the dispersion and dilution with distance from the source will have some attribute of a 2-dimensional or 3-dimensional radial spread. Thus, as a simplistic model, dilution will be proportional to at least the square of distance from the source. If one sampled this space randomly, one would find many more low concentrations than high concentrations, which is the skew indicative of lognormal distributions.

In this report, the frequency distributions of concentrations for each radionuclide were examined, and either the linear, normal frequency histogram (with concentration on the x axis) or the lognormal frequency histogram (with log concentration on the x axis) is shown, depending on the best fit. For a few radionuclides, both are shown because both describe the data well.

1.7   ISOTOPE RATIOS

Along with simple environmental concentrations, there is useful information to be obtained from isotope ratios. Isotope ratios for members of decay chains are critically important, because inevitably some of the decay-chain radionuclides are very difficult to detect at environmental concentrations. In fact, many of the analyses reported in the literature for U, Ra and Th are from measurements of their decay progeny assumed to be in secular equilibrium with the parent radionuclide. However, as highlighted by Sheppard et al. (2008), several parent/progeny pairs are not in secular equilibrium in environmental samples, because they have different environmental mobilities. In these cases, because of the need to estimate concentrations, it is even more important to document how the activity concentration ratios vary among media. For example, it may be possible to estimate concentrations of decay chain members even if there is no secular equilibrium, as long as the activity ratios are predictable.

Isotope ratios are also important for non-chain radionuclides such as ^{14}C, ^{36}Cl and ^{129}I. An illustration is the tracking of ^{129}I from Sellafield and La Hague into the Baltic Sea (Nies et al. 2000) and onto Scandinavian soils (Aldahan et al. 2006). The ^{129}I is very difficult to detect, but it is not dissociated from stable ^{127}I in environmental processes. Therefore, once an ^{129}I/^{127}I ratio for a region is determined, then the concentrations of ^{129}I can be inferred from data on ^{127}I. Of course, this requires detailed interpretation of the transport pathways for iodine, since the assumption is of uniform isotopic mixing and iodine is selectively retained in some media. The key point here is that isotope ratios compiled for even a few background sites will facilitate estimation of concentrations of the difficult-to-detect radionuclides in a much broader range of sites.

2. METHOD OF REVIEW

2.1   SEARCH METHODS

The initial literature search was completed using the SCOPUS and ScienceDirect databases. These cover a broad range of literature, including disciplines such as geomorphology[8] and archaeometry[9] as well as the classical environmental sciences. Each radionuclide was used as a search term along with geographic terms such as Canada, Ontario, and boreal. Once key papers were identified, citation searches were done to locate papers that subsequently cited these papers. Similarly, the papers cited by key papers were considered.

A list of key authors was identified and searches were done for their papers. A few of these were also contacted directly to enquire about more recent work or papers that may have been missed.

In addition to papers listed in scientific databases, there was an effort to obtain 'grey' literature sources. The most important of these were pre-operational and monitoring reports for Canadian nuclear facilities. Of these, only reports from 2007 or 2008 were used to avoid reporting repeated measures of the same sites, and only control or reference sites used. In general, these reports were supplied by the site owners, and many were available on line.

2.2   CORRECTION OF ERRORS

In the process of the review, a relatively large number of papers and reports were found to have errors, generally of two types. The most common were errors of 10^3-fold resulting from faulty unit conversions. In at least one case, word processing software used by the author's institute converted the unit prefix µ to m. The next most common error was a transposition of tables or figures. These types of errors were evident when the data were compared to other papers by the same authors or from the same sampling locations. Where possible, the author was contacted to confirm our interpretation of the error. Alternatively, some papers and reports would have the error in one place and the correct value in another place, or another paper, so this confirmed our interpretation. Any assumptions that were not confirmed are noted.

2.3   CONVERSION FACTORS

A number of conversion factors were needed because values in the literature were not always presented in the same way as in this report. Some of these conversions are not simple unit conversions, so they are described here.

Data for ^{14}C are frequently reported as percent of modern carbon (PMC), where 'modern' is taken to mean pre-industrial age, about 1890, ^{14}C and stable C levels which are then decay

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[8] Geomorphology is the study of landforms, and in some studies this can involve radiochemical analysis to determine the age of materials.

[9] Archaeometry is the application physical, chemical and radiochemical analytical techniques to archaeology

corrected to 1950. During the industrial age, massive amounts of geological-age C containing little ^{14}C were released to the biosphere as emissions from the combustion of fossil fuels. This diluted biosphere ^{14}C which is normally sustained by cosmogenic production. Conversely, the atmospheric nuclear bomb tests and releases from power reactors have elevated ^{14}C levels since about 1963. There is also some variation in the reference material used for PMC, but here we assume 100% PMC refers to 226 Bq per kg C, a value common among those found in the literature. Thus, a value reported as 110% PMC would have 249 Bq per kg C.

The half-life of [40]K is so long (1.28×10^9 a) that it is assumed to represent a constant 0.012% by mass of total K, so that natural K is assumed to have a specific activity 31 Bq per g K. Similarly, [87]Rb has a very long half-life (4.9×10^{10} a), and is present at a nearly constant 27.83% fraction of total Rb, resulting in 860 Bq per g Rb.

Very often, the data reported in the literature for [36]Cl and [129]I are expressed as atoms per unit media or atom ratios. Similarly, ^{3}H is often expressed in tritium units (TU) and [36]Cl in 'chlorine units' (CLU). The conversions are straightforward, based on half-life and atomic mass, but are given here for convenience.

For [3]H:

$$1.8 \times 10^{-9} \text{ Bq per atom of } [3]\text{H}$$

One TU is 1 atom ^{3}H per 10^{18} atoms [1]H

One TU in water is 0.199 Bq L^{-1} (water is 111.1 mole H per L)

For [36]Cl:

$$7.3 \times 10^{-14} \text{ Bq per atom of } [36]\text{Cl}$$

One CLU is 1 atom [36]Cl per 10^{15} atoms [35,37]Cl

For a unit atom ratio ([36]Cl/[35,37]Cl), it implies 1.2×10^9 Bq per g Cl

For [129]I:

$$1.4 \times 10^{-15} \text{ Bq per atom of } [129]\text{I}$$

For a unit atom ratio ([129]I/[127]I), it implies 6.4×10^6 Bq per g I

Various conversions have been reported in the literature for [nat]U, differing by the assumed contribution of [235]U. For example, Ahier and Tracy (1997) assumed [235]U was present at 5% of the mass of [238]U for emissions from a fuel processing facility. More typically, it is assumed that [235]U is present at 0.72% of the mass of [238]U (Veska and Eaton 1991). These conversions follow from the half-lives and relative abundances of the isotopes, we reference Veska and Eaton (1991) simply as verification of the final specific activity.

For [nat]U:

12.4 kBq from ^{238}U per g ^{238}U or per g ^{nat}U

25.0 kBq from ^{234}U, ^{235}U, and ^{238}U per g ^{238}U or per g ^{nat}U, assuming secular equilibrium between ^{234}U and ^{238}U and ^{235}U present at 0.72% of the mass of ^{238}U.

0.566 kBq from ^{235}U per g ^{238}U or per g ^{nat}U

0.045 Bq from ^{235}U per Bq from ^{238}U

Two further conversions were used and are somewhat empirical - the conversion between organic C and organic H content of soils and organic matter content. In general, soil organic matter has 1.72- to 2.0-fold more mass than soil organic C (Nelson and Sommers 1996): that is the organic matter is about 50% to 58% C. Similarly, soil organic matter is about 5% H, and the H/C ratio is about 0.1.

2.4   OUTLINE OF THE REPORT

The body of the report deals with the following radionuclides, in this order of increasing atomic mass:

^{3}H, ^{14}C, ^{36}Cl, ^{40}K, ^{90}Sr, ^{87}Rb, ^{129}I, ^{137}Cs, ^{210}Bi, ^{210}Pb, ^{210}Po, ^{222}Rn, ^{223}Ra, ^{224}Ra, ^{226}Ra, ^{227}Ac, ^{227}Th, ^{228}Ra, ^{228}Th, ^{230}Th, ^{231}Pa, ^{231}Th, ^{232}Th, ^{234}Th, ^{234}U, ^{235}U and ^{238}U.

These include the radionuclides indicated in the objectives, plus progeny with half-lives longer than 1 d. Progeny with shorter half-lives are assumed to be in secular equilibrium and the corresponding doses for these are often included in the dose conversion factors for the parent radionuclide.

No specific data were found for ^{210}Bi, ^{223}Ra, ^{224}Ra, ^{227}Ac, ^{227}Th, ^{231}Th and ^{234}Th. Their activity concentrations can be related to their parents, based on secular equilibrium. Because their half-lives are short, most <0.06 a, it is reasonable to assume that even in environmental media these radionuclides are in secular equilibrium with their parents. For ^{210}Bi, even the radioanalytical methods rely on the assumption of secular equilibrium, because ^{210}Bi is measured as a surrogate for ^{210}Pb.

The environmental data for ^{14}C, ^{36}Cl and ^{129}I include direct measures of activity concentration, but are dominated by specific activity data. As a result, representative data for stable element concentrations were also compiled. For ^{3}H (T), most of the data compiled were activity concentrations in water, and assuming this to be HTO (tritiated water with one tritium atom per molecule), this is analogous to specific activity data in that the ^{3}H concentration in organic media could be computed assuming the organically bound tritium (OBT) has the same specific activity as water.

Many of the data in the literature for U refers to ^{nat}U, in part because many of the analyses are based on chemical as opposed to radiochemical methods. This ^{nat}U includes ^{234}U, ^{235}U, and ^{238}U. By mass, ^{nat}U and ^{238}U are identical because ^{234}U and ^{235}U contribute negligible mass. By activity, ^{nat}U has about twice the specific activity of ^{238}U because of the contributions of ^{234}U and ^{235}U.

Maps of the distributions of ^{40}K, ^{232}Th and ^{238}U have been prepared by Department of Natural Resources Canada and are shown in Appendix B.

The report is supported by an Excel database. The key parameters listed in the database are sample media (mostly soil versus water), activity concentration or specific activity, mass concentration of the element, reference source and a description of how the specific values were derived from the reference.   In addition, the data were categorized for spatial relevance. Notes were also included where possible about analytical methods, detection limits and statistical variation in the activity concentrations. Qualitative indices were included in many cases to rate the quality and relevance of the analytical and sampling methods. Appendix C shows the more important fields from the database.

The database includes values below the detection limit (DL). In general, for the statistical summaries these were substituted by the DL concentration. The exceptions were where the DL reported was markedly higher than the concentrations reported by other authors, in which case the DL were not included in the summations. The database also includes a few values that were not specifically identified by the authors as contaminated, but had high concentrations and were geographically in a position where contamination was plausible. Although included in the database, these are identified as outliers and were not included in the statistical summaries.

3. ENVIRONMENTAL CONCENTRATIONS

3.1 TRITIUM (^{3}H)

Tritium (^{3}H) is produced in the atmosphere by the interaction of cosmic-ray produced neutrons with nitrogen, with a production rate of 5000 ± 3000 atoms m^{-2} s^{-1} (Vertes et al. 2003). There is also natural production in the atmosphere resulting from solar emissions. Once created in the atmosphere, the ^{3}H typically becomes incorporated into water and can reside in the lower stratosphere for 1 to 10 years. Once it enters the troposphere, rainout will occur within a few days (Vertes et al. 2003). Michel et al. (1984) and Renaud et al. (2005) indicated that ^{3}H in rain before the atmospheric bomb test era would have been 3-5 Bq L^{-1}, and presumably this would represent present natural production rates. Fallout ^{3}H and releases from nuclear reactors and particle accelerators add to these natural sources. Although there can be considerable isotopic discrimination of ^{3}H in biological processes compared to the relatively much lighter stable ^{1}H, the specific activity of natural ^{3}H in soils and surface waters is relatively uniform across the landscape. Thus, nation-wide (or global) summaries are appropriate.

There are data for ^{3}H in free water of tissues (fish, plants and milk), and of these the average concentration (n = 6) was 4.0 Bq L^{-1}. Water with pre-fallout concentrations that have further decreased by radioactive decay can be found at depth, an example being the 0.12 Bq L^{-1} reported in Sturgeon Falls Ontario by Renaud et al. (2005)[10].

The ^{3}H concentrations in surface water and shallow wells (recently meteoric) were strongly skewed, and were still skewed after log transformation (Figure 3-1). Although care was taken to exclude tritiated water that was contaminated by power reactor releases, these releases mix in lakes and are detectable at considerable distances from the source. Conversely, because of the relatively short half-life (12.33 a), drinking water obtained from deep wells may be depleted in ^{3}H because of decay[11].

Spatially, ^{3}H is gradually mixed by way of the hydrological cycle. However, the lower Great Lakes (Huron, Erie and Ontario) had concentrations of about 4.4 Bq L^{-1} compared to 3.2 Bq L^{-1} in Lake Superior and 3.9 Bq L^{-1} in the Ontario portions of the Canadian Shield. Farther from the Great Lakes, concentrations were lower: 1.8 Bq L^{-1} in western Canada and 1.6 Bq L^{-1} in eastern Canada. This may be an effect of the power reactors on the lower Great Lakes. Arctic Canada had high concentrations measured before the early 1980's, averaging 23 Bq L^{-1}, but the Mackenzie River was 1.8 Bq L^{-1} in 2010. It may be the earlier measurements in the arctic were of fallout ^{3}H, and if so decay corrected to 2010 this would be 4 Bq L^{-1}, more in line with present-day measurements.

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[10] This datum is not included in the numerical summaries.

[11] The data set is almost exclusively surface water, the only possible exceptions are a few sources that were described as municipal drinking water, and these may include well water. None of these were distinctly depleted in ^{3}H, and so all were considered representative of surface or meteoric water.
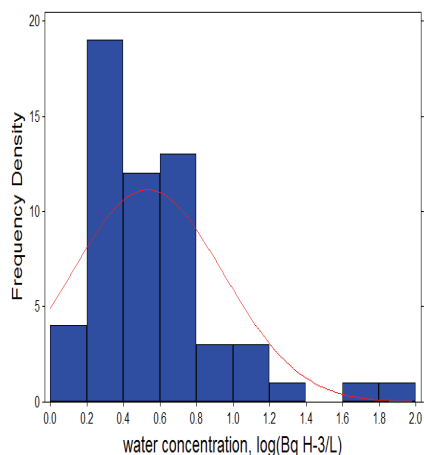
Figure 3-1: Frequency histogram of ^{3}H concentrations in precipitation, surface, shallow well and drinking water (n = 57). The red line is the best-fit lognormal frequency curve.

Of the 57 observations compiled, the values were:

Minimum	0.12 Bq L^{-1}
Median	3.0 Bq L^{-1}
Maximum	45 Bq L^{-1}
Geometric mean (GM)	3.2 Bq L^{-1}
Geometric standard deviation (GSD)	2.3
Implied EI (GM x (GSD - 1))	4.2 Bq L^{-1}

This GM of 3.2 Bq L^{-1} in water can be expressed as a specific activity of 29 Bq (kg H)$^{-1}$, assuming 111.1 g H L^{-1} water. These levels are very comparable to the estimates of pre-bomb meteoric water (above), suggesting that these levels are largely of natural as opposed to anthropogenic origin.

No ^{3}H data were found for Canadian soils. For soils in the field, much of the ^{3}H present may be in the soil pore water, with less in OBT as part of the soil organic matter.

Soil concentrations in this report are based on the dry weight of soil. Thus, there is essentially no HTO in dry soil and the concentration would be 0 Bq kg^{-1} dry soil. However, at field moisture content, assuming an average soil moisture content of 15% water per mass of moist soil, the GM of 3.2 Bq L^{-1} in water would imply a concentration in moist soil of 0.5 Bq kg^{-1} moist soil. This is clearly very transient, and has little biological relevance because organisms intake ^{3}H largely with water ingestion and so the concentration in water is the important parameter. The OBT in soil organic matter is less transient and remains in dry soil, but is rarely reported. Soil organic matter is composed of materials of varying age, up to centuries. Thus, radioactive decay of ^{3}H significantly affects the net OBT content of soils. Assuming 12 g organic C per kg dry soil (referenced in the next section), an H/C ratio of 0.1 and a specific activity of 29 Bq (kg H)$^{-1}$, GM of 3.2 Bq L^{-1} in water implies a concentration in dry soil, as OBT, of 0.03 Bq kg^{-1} dry soil. The actual value will be somewhat different than this depending on the average age of the soil organic matter. Again, this OBT has little biological relevance, even for soil organisms.

3.2   CARBON-14

Carbon-14 is also naturally produced in the atmosphere by impact of cosmic-ray neutrons on nitrogen, where the ^{14}C then either reacts with oxygen or undergoes isotopic exchange to form ^{14}CO or ^{14}CO$_2$ molecules. The production rate is about 18000 atoms m^{-2} s^{-1} (Whicker and Schultz 1982). These molecules follow the same reactions as their stable-element counterparts in the atmosphere and biosphere, although often there is discernable isotopic discrimination in rate-limited processes because the heavier ^{14}C molecules have slightly slower diffusion and reaction rates (Vertes et al. 2003). Because gaseous species are the dominant dispersal form, nation-wide (or global) summaries of spatial distribution of ^{14}C are appropriate.

Almost all the data compiled for ^{14}C were specific activities, and these are probably the best representation of ^{14}C in the biosphere. Essentially all organic C in the biosphere comes from recent photosynthetic activity, and so the specific activity in the atmosphere is permutated throughout the biosphere. The C content of organic matter is relatively constant, but the C content of water and soil can be quite variable. It is better to determine a specific activity for ^{14}C in the environment in general and apply this to soils and waters of concern using data for stable C concentrations.
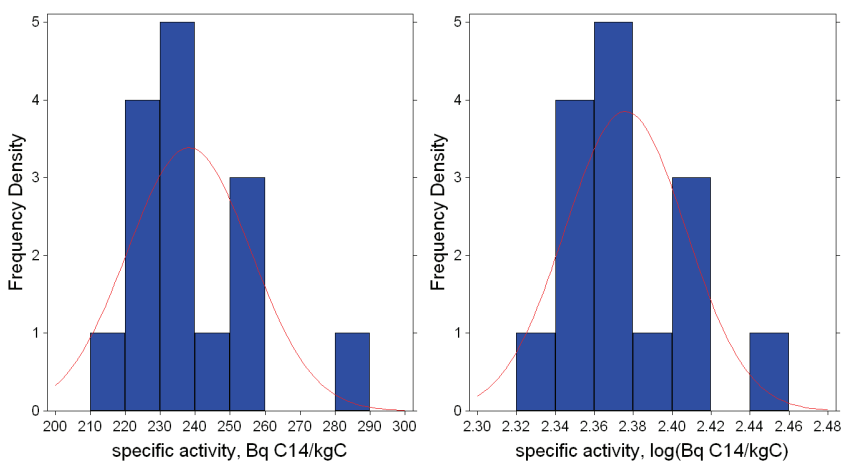
Figure 3-2: Frequency histograms of specific activities of ^{14}C in various environmental media (n = 15). The red lines are the best-fit normal and lognormal frequency curves.

The specific activity data appear skewed, even after log transformation (Figure 3-2). Of the 15 observations compiled, the values were:

Minimum	218 Bq (kg C)$^{-1}$
Median	233 Bq (kg C)$^{-1}$
Maximum	283 Bq (kg C)$^{-1}$
Geometric mean (GM)	239 Bq (kg C)$^{-1}$
Geometric standard deviation (GSD)	1.07
Implied EI (GM x (GSD - 1))	17 Bq (kg C)$^{-1}$

Given that 100 PMC is 226 Bq (kg C)$^{-1}$, this median observed specific activity of 233 Bq (kg C)$^{-1}$ suggests that the present levels of ^{14}C are representative of natural background despite the time-varying modern inputs of ^{14}C and cold (fossil) stable C.

Concentrations (by mass) of organic stable C in soils can range from nearly 0% in sandy soils to nearly 50% in organic soils. The median for 27,000 mineral soils (Soil Landscapes of Canada, 2009) was 12 g organic C per kg (1.2%), and for 1500 organic soils (soils with greater than 30% organic matter) was 400 g organic C per kg (40%). The GSD for soil organic carbon was 2.7. Soils may contain carbonate minerals, but in general these contain ancient 'cold' C, and little ^{14}C. Some of the organic C in soil may also be up to several centuries old, and so the overall specific activity may be slightly different than the present atmospheric specific activity. Based on these organic C contents of soils and the assumption that the atmospheric specific activity applies, median ^{14}C levels in mineral soils would be 3 Bq kg dry soil and in organic soils would be 100 Bq kg^{-1} dry soil.

Concentrations of organic stable C in water differ by at least 5-fold, from the brown-coloured water of small boreal lakes to the relatively clear Great Lakes. From Smith et al. (2004), the Great Lakes typically have 2.8 mg organic C per L, with tributary rivers having 8 mg organic C per L. Boreal lakes have levels of about 10 mg organic C per L (Heikkinen 1994, Jonsson et al. 2007 and O'Driscoll et al. 2006). The GSD for each of these studies was in the range of 1.3 to 1.6. Surface waters will also contain inorganic C, typically as carbonate species and thus highly dependent on pH, photosynthetic activity and respiration, but probably in isotopic equilibrium with the atmosphere. Based on these organic C contents and the specific activity of 239 Bq (kg C)$^{-1}$, typical ^{14}C levels in surface waters would be 0.0007 to 0.002 Bq L^{-1}.

3.3 CHLORINE-36

Cosmic-ray neutron capture (spallation) of Ar in the upper atmosphere accounts for much of the natural atmospheric inventory of ^{36}Cl (Fabryka-Martin et al. 1987). These authors suggest the residence time in the troposphere is 2 weeks or less, so that global mixing is not complete. Deposition, both wet and dry, is about fivefold greater at about 45° latitude that at the equator. The oceans have negligible ^{36}Cl, so that the specific activity of ^{36}Cl increases exponentially inland from the coast (Fabryka-Martin et al. 1987), with atom ratios ranging from 10^{-14} along the coast to 10^{-12} inland (0.01 to 1 Bq (kg Cl)$^{-1}$). Fallout was an important spike in ^{36}Cl production, and this is evident in Cl that was chemically bound (isolated from exchange reactions) at that time.

Cosmogenic ^{36}Cl also arises because of thermal neutron, epithermal neutron, spallation (fast neutron) and muon-absorption reactions in rocks (Gosse and Phillips 2001, Heisinger and Nolte 2000, Swanson and Caffee 2001), all of which vary in intensity with depth in the rock and the concentrations of calcium and potassium. Natural (geogenic) neutron activation of ^{35}Cl and alpha interaction with ^{33}S and ^{39}K to produce ^{36}Cl also occurs. Reference texts by Whicker and Shultz (1982) and Vertes et al. (2003) suggest that the atmospheric cosmogenic ^{36}Cl is deposited to the Earth's surface at about 12 atoms m^{-2} s^{-1}. With an annual net rainfall (minus evaporation) of 0.1 m to 1 m, this is a concentration in the range of 3 x 10^{-7} to 3 x 10^{-8} Bq L^{-1} as a result of natural processes. Andrews and Fontes (1991) estimated that the natural deposition in relatively dry western Canada resulted in a soil water concentration of 2 x 10^{-7} Bq L^{-1}.

There is a considerable body of research reporting [36]Cl concentrations in exposed rocks, done to determine how long, in millennia, that the rock has been exposed on the surface (e.g. Jackson et al. 1999, Osborn et al. 2007). This [36]Cl is locked in the rock matrix (otherwise it would have no value for dating events), and has no biological significance. The specific activities in surface rocks from Jackson et al. (1999) and Osborn et al. (2007) had a median of 0.24 Bq (kg Cl)[-1], which is very low compared to current biosphere data.

No data were obtained for [36]Cl in Canadian soil. There were several studies reporting specific activities in tissues, including teeth, bone and plants. Paleological teeth and bones and pre-fallout seeds had values of about 1.7 Bq (kg Cl)[-1] (Cornett et al. 1997b). Plant samples after the fallout had about 32 Bq (kg Cl)[-1], because of [36]Cl in the fallout.

Specific activities were more commonly reported for waters, including present day surface waters and borehole waters that may predate fallout. The range of specific activities in present day surface waters was substantial, and only one study that reported pre-fallout borehole waters had lower specific activities of about 0.02 Bq (kg Cl)[-1].
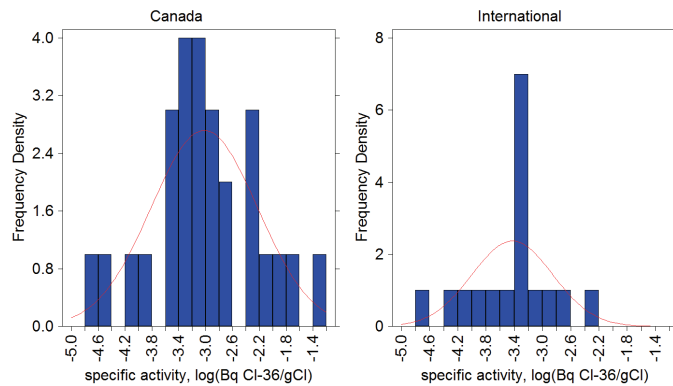
Figure 3-3: Frequency histograms of specific activities of [36]Cl in various environmental media, data for Canada (n = 27) and international (n = 17). The red lines are the best-fit lognormal frequency curves.

The specific activity data appear to conform to lognormal (Figure 3-3). Of the 27 observations of Canadian environmental media, the values were:

Minimum	0.020 Bq (kg Cl)[-1]
Median	0.70 Bq (kg Cl)[-1]
Maximum	40 Bq (kg Cl)[-1]
Geometric mean (GM)	0.96 Bq (kg Cl)[-1]
Geometric standard deviation (GSD)	6.2
Implied EI (GM x (GSD - 1))	5.0 Bq (kg Cl)[-1]

The specific activity data among the 17 international observations were:

Minimum	0.025 Bq $(kg\ Cl)^{-1}$
Median	0.44 Bq $(kg\ Cl)^{-1}$
Maximum	4.7 Bq $(kg\ Cl)^{-1}$
Geometric mean (GM)	0.37 Bq $(kg\ Cl)^{-1}$
Geometric standard deviation (GSD)	3.7

Comparing the Canadian and international GM values for specific activity, they are within one GSD, and so could not be considered statistically different. The Canadian data may be slightly elevated because several of the samples were drawn from eastern Ontario, and they may have been influenced by emissions from the Chalk River Nuclear Laboratory. Several of these slightly higher values were water from tissue samples, but it is not likely that they were high because of biological effects.

The specific activities in paleological teeth and bones and pre-fallout seeds were about 1.7 Bq $(kg\ Cl)^{-1}$ (Cornett et al. 1997b), comparable to the modern values. This suggests the observed specific activities represent natural background.
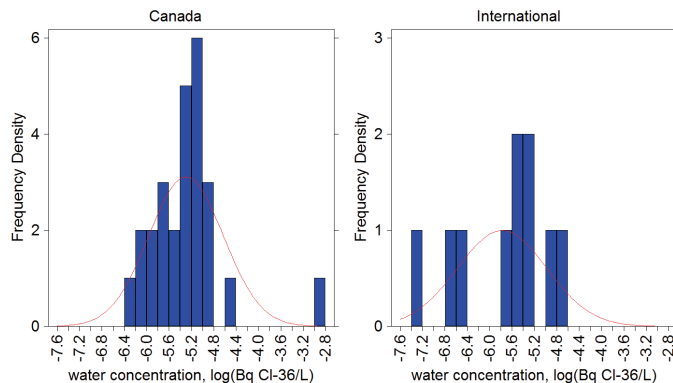
Figure 3-4: Frequency histograms of concentrations in surface, shallow well and precipitation, data for Canada (n = 26) and international (n = 10). The red lines are the best-fit lognormal frequency curves.

The concentrations of ^{36}Cl in water for samples from Canada also appear to conform to lognormal (Figure 3-4). Of the 26 observations compiled, the values were:

Minimum	4.4×10^{-7} Bq L^{-1}
Median	5.1×10^{-6} Bq L^{-1}
Maximum	1.5×10^{-3} Bq L^{-1}
Geometric mean (GM)	5.1×10^{-6} Bq L^{-1}
Geometric standard deviation (GSD)	4.6
Implied EI (GM x (GSD - 1))	1.8×10^{-5} Bq L^{-1}

The concentrations of ^{36}Cl in water from the 10 international samples (Figure 3-4) were:

Minimum	6.0×10^{-8} Bq L^{-1}
Median	2.9×10^{-6} Bq L^{-1}
Maximum	2.0×10^{-5} Bq L^{-1}
Geometric mean (GM)	1.7×10^{-6} Bq L^{-1}
Geometric standard deviation (GSD)	6.3

The difference in GM between the international and Canadian water concentration data were well less than one GSD, and so are not statistically different. Similarly, there were no statistically significant differences or notable trends spatially among the data, suggesting that global averages may be representative. These median concentrations are about an order of magnitude higher than the 2×10^{-7} Bq L^{-1} that Andrews and Fontes (1991) estimated for natural deposition from the atmosphere. These authors also estimated concentrations of ~7×10^{-6} Bq L^{-1} in near-surface groundwater as a result of terrestrial cosmogenic production. The later are comparable to the median observed concentrations, suggesting that the median concentrations may represent natural background, largely of terrestrial cosmogenic origin.

The relatively high GSD for ^{36}Cl was also evident in the variation reported within studies. The specific activities had GSD values in the range of 1.1 to 5, and the water concentrations had GSDs in the range 1.1 to 10. Some of this variation may be because of inclusion of fallout or pre-fallout waters (well waters) and continued isotopic dilution of fallout ^{36}Cl. Analysis for ^{36}Cl is complicated, and so analytical difficulties may contribute to this variability.

Concentrations of stable Cl are not commonly measured in soils – there is sufficient for plant growth in all regions except a few locations in the Prairies, and it is rarely a contaminant of concern. Sheppard et al. (1999), Hill (1986) and Edwards et al. (1981) gave values with a median of about 50 mg kg^{-1} and a GSD of about 2.2. In recent sampling in Northern Ontario and Manitoba, the GM was 230 mg kg^{-1} with a GSD of 1.6 (Sheppard et al. 2009a). These values may not be statistically different, and it is not clear why they would be different. From the value 230 mg kg^{-1} and the specific activity of 1.0 Bq (kg Cl)$^{-1}$, the corresponding concentration in soil would be 0.0002 Bq kg^{-1} dry soil.

Concentrations of stable Cl are measured more commonly in water in order to monitor the effects of road salt and general human activities. The concentrations in the Great Lakes have increased from a GM of 1.6 mg L^{-1} prior to settlement to 12 mg L^{-1} recently (Chapra et al. 2009). There is also an increase from 1.4 mg L^{-1} in Lake Superior to 22 mg L^{-1} in Lake Ontario, reflecting more anthropogenic inputs downstream and a general evaporative concentration of Cl with time. Hayashi et al. (1998), Andrews and Fontes (1993) and Cornett et al. (1997a) noted concentrations in precipitation of about 0.25 mg L^{-1}. The median concentration in 21 rivers sampled across Canada in 2010 (Sheppard and Sanipelli 2011) was 7.6 mg L^{-1}. From these 21 values and the specific activity from 4 of these sites of about 0.3 Bq (kg Cl)$^{-1}$, the corresponding median concentration would be 2×10^{-6} Bq L^{-1}, very close to the GM of measured concentrations.

3.4   POTASSIUM-40

Potassium-40 is a primordial radionuclide, and is neither the product nor parent of a decay series. Because of the very long half-life (1.28×10^9 a), measures of ^{40}K are assumed to be

directly correlated to measures of stable K. The corresponding specific activity is 31 kBq (kg K)$^{-1}$, and this is representative of natural background. The variation in ^{40}K concentrations is therefore the variation in total stable K concentrations. For this reason, and in contrast to most other radionuclides, ^{40}K concentrations might be expected to be normally distributed. This is evident for soil concentrations in Figure 3-5: both linear and log-transformed ^{40}K concentrations appear to represent the data well.
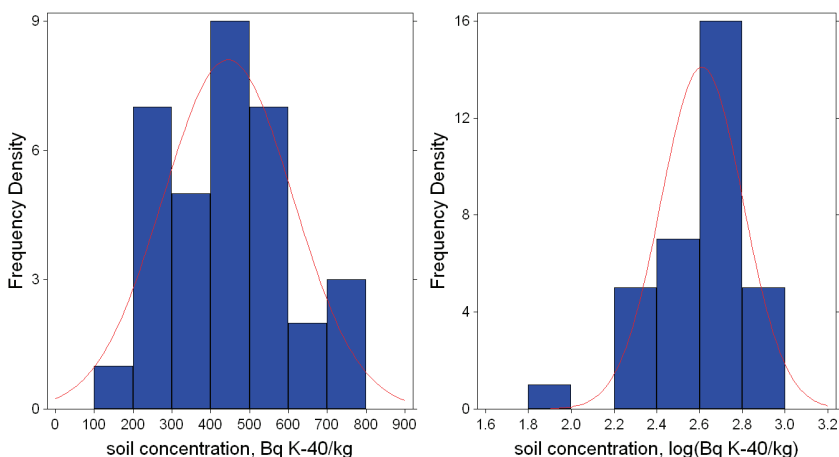
Figure 3-5: Frequency histograms of ^{40}K concentrations in soil (n = 34). The single low value is an organic soil. The red lines are the best-fit normal/lognormal frequency curves.

In soils, K concentration is related to clay content. De Jong et al. (1994) proposed the empirical relationship ^{40}K (Bq kg^{-1}) = 385 (Bq kg^{-1}) + 3.7·clay (%). VandenBygaart et al. (1999) proposed empirical relationships of ^{40}K (Bq kg^{-1}) = 420 (Bq kg^{-1}) + 7.88·clay (%) and ^{40}K (Bq kg^{-1}) = 259 (Bq kg^{-1}) + 5.37·clay (%) for soils of different depositional regimes. Maps of ^{40}K concentrations across Canada are shown in Appendix B. Several studies reported ^{40}K concentrations in beach sands, with a range similar to that of mineral soils (Figure 3-5). Zach et al. (1989) reported concentrations in an organic soil of 100 Bq kg^{-1}.

Of the 33 observations of ^{40}K concentrations in mineral soils (i.e. excluding the soil of Zach et al. 1989), the values were:

Minimum	200 Bq kg^{-1}
Median	460 Bq kg^{-1}
Maximum	769 Bq kg^{-1}
Geometric mean (GM)	430 Bq kg^{-1}
Geometric standard deviation (GSD)	1.5
Implied EI (GM x (GSD - 1))	210 Bq kg^{-1}

The GSD for ^{40}K is relatively low, and this was also reflected in the individual studies where the range in GSD was 1.1 to 1.6.

Water concentrations of ^{40}K are rarely reported: the average of two studies that reported values is 0.08 Bq L^{-1}. However, Rowan and Rasmussen (1994) did a thorough review of surface water

stable K concentrations, and from these it is possible to compute ^{40}K concentrations. Also, Sheppard and Sanipelli (2011) measured stable K at 21 sites. There were distinct spatial trends, much the same as for stable Cl. Lake Superior and the North Channel had concentrations of about 18 mBq L^{-1}, and concentrations increased downstream with 28 mBq L^{-1} in Lake Huron, 44 mBq L^{-1} in Lake Erie and 64 mBq L^{-1} in Lake Ontario. This is suggestive of more human inputs and more concentration by evaporation downstream. The Ontario Shield had low concentrations of about 23 mBq L^{-1}, perhaps because the watersheds are smaller and more northerly and remote. The concentrations in western Canada was quite high (60 mBq L^{-1}), which is consistent with it being the recipient of a very large and relatively arid watershed. Overall, the data were skewed, even after log transformation (Figure 3-6).
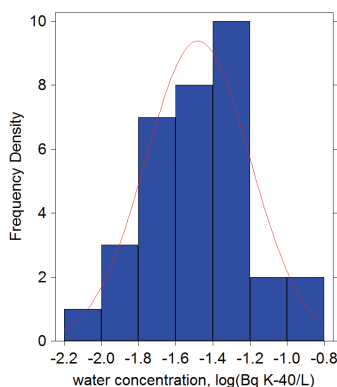
Figure 3-6: Frequency histogram of ^{40}K concentrations in surface waters (n = 33), largely based on data for stable K. The red line is the best-fit lognormal frequency curve.

Of the 33 observations and estimates of ^{40}K concentrations in surface waters, the values were:

Minimum	0.009 Bq L^{-1}
Median	0.034 Bq L^{-1}
Maximum	0.11 Bq L^{-1}
Geometric mean (GM)	0.033 Bq L^{-1}
Geometric standard deviation (GSD)	1.9
Implied EI (GM x (GSD - 1))	0.030 Bq L^{-1}

3.5   RUBIDIUM-87

Rubidium-87 is a primordial radionuclide with a very long half-life (4.9 x 10^{10} a), and so virtually does not decay and is present at a nearly constant 27.83% fraction of total Rb. The resulting specific activity is 860 kBq (kg Rb)$^{-1}$, and this is representative of natural background. Thus, the relevant data are for stable Rb concentrations in soils and surface waters. Rubidium is easily measured, but not often reported because it is rarely linked with contamination or biological responses.

In a survey of 30 soils in Manitoba and Ontario, Sheppard et al. (2009a) found total Rb concentrations of 37 ±18 mg kg^{-1}. A separate database reported by Sheppard et al. (2009b) involved 171 soils from southern Ontario, and the Rb concentrations were approximately normally distributed with a mean and standard deviation of 29 ±14 mg kg^{-1}. In activity

concentration of ^{87}Rb, assuming 27.83 % of Rb is ^{87}Rb, this is 25 ± 12 Bq kg^{-1}. The corresponding relative standard deviation implies an EI of 12 Bq kg^{-1}.

In survey2 of 20 lakes and 21 rivers, Sheppard et al. (2009a) and Sheppard and Sanipelli (2011) found Rb concentrations with a GM of 0.29 µg L^{-1} (GSD = 3.4) In activity concentration of ^{87}Rb, this is 0.26 mBq L^{-1}. The corresponding EI is 0.62 mBq L^{-1}.

3.6   STRONTIUM-90

Strontium-90 is a fission product, and apart from a small amount of natural spontaneous fission, the dominant sources of ^{90}Sr are nuclear reactors and fallout. Measurement of ^{90}Sr is complicated because it requires chemical separation prior to analysis. Additionally, it is often associated with ^{137}Cs during emissions and deposition, which is simpler to measure and so serves as a surrogate. Barrie et al. (1992) measured ^{90}Sr deposition in a south-north transect, noting a decrease northward. Assuming a 15-cm depth of soil with a dry bulk density of 1300 kg m^{-3} and decay adjusting to 2010, the concentrations were 2.9 Bq kg^{-1} at 60-70°N decreasing to 0.55 Bq kg^{-1} at 80-90°N. As a measure of variation, the GSD for ^{137}Cs of 3.5 may be a useful surrogate, giving an EI of 7.3 Bq kg^{-1}.

Strontium-90 is measured more commonly in surface waters, and contamination from present nuclear facilities such as Chalk River Laboratories is notable at least within 100 km downstream. Because the half-life is relatively short (29 a) and much of the ^{90}Sr present is the result of deposition from fallout, there is a question of whether or not to adjust for decay to a specific year. For waters, this is especially true because the watersheds continue to contribute ^{90}Sr to the water, so the source to the water is not just directly from the initial fallout pulse. Thus, the rate of change in water concentrations is not a simple first-order function of sediment burial, flushing and decay, but is at least second-order because of the input from the watershed. In effect, the ^{90}Sr from the watershed is a delayed pulse of fallout to the water. Tracy and Prantl (1983) presented environmental half-times to estimate future ^{90}Sr concentrations, with values of 20 a for Lake Superior and 10 a for Lake Huron. Most of the ^{90}Sr data were reported in the 1980's and early 1990's, so reductions of 50% since then may have occurred.
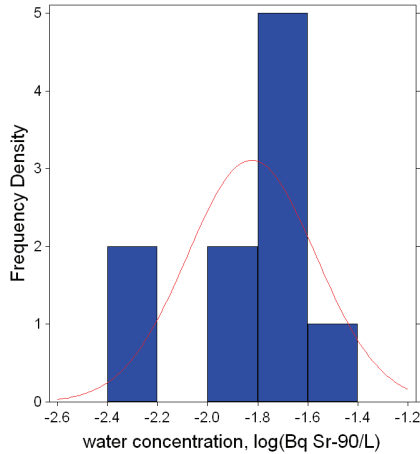
Figure 3-7: Frequency histogram of ^{90}Sr concentrations in surface waters (n = 10). The red line is the best-fit lognormal frequency curve.

Of the 10 observations of ^{90}Sr concentrations in surface waters, the values without any decay or loss adjustment were:

Minimum	0.0044 Bq L^{-1}
Median	0.018 Bq L^{-1}
Maximum	0.026 Bq L^{-1}
Geometric mean (GM)	0.015 Bq L^{-1}
Geometric standard deviation (GSD)	1.8
Implied EI (GM x (GSD - 1))	0.012 Bq L^{-1}

As noted above, these ^{90}Sr levels are due to human activities, specifically fallout, and probably overstate current Canadian levels.

3.7   IODINE-129

Cosmic-ray activation of Xe in the upper atmosphere accounts for much of the natural atmospheric inventory of ^{129}I, with a contribution up to 50% from volatilization of geogenic ^{129}I (Fabryka-Martin et al. 1987). Beer (2004) indicated production in the atmosphere was 0.3 atoms m^{-2} s^{-1}, about 40-fold lower than ^{36}Cl. Fabryka-Martin et al. (1987) suggest the residence time in the troposphere is 2 weeks or less, so that global mixing is not complete. Deposition, both wet and dry, is about fivefold greater at about 45° latitude that at the equator. Residence times of ^{129}I and stable I in the oceans is sufficiently long, and the interchange with the atmosphere sufficiently rapid, that the oceans buffer the atmospheric ^{129}I:I atom ratio to a fairly constant natural background value of 3 x 10^{-13} to 3 x 10^{-12} (0.002 to 0.02 Bq (kg I)$^{-1}$) (Fabryka-Martin et al. 1987). These levels are consistent with pre-bomb or natural specific activities as reported by Hou et al. (2009), Kekli et al. (2003) and Renaud et al. (2005). None the less, ^{129}I from fallout was an important spike in production and is evident in groundwater that recharged during that time.

Iodine-129 also arises naturally from spontaneous fission in rocks, which can be estimated from the U content. The spontaneous fission decay constant was assumed to be 8.49 x 10^{-17} a^{-1} by

Fabryka-Martin et al. (1991), and the fission yield was assumed to be 0.05%. Thus, there are 2500 atoms [129]I produced per year per µg U. However, much of this remains trapped in the solid matrix. The 'escape efficiency' (the fraction of fission [129]I that escapes the solid matrix and interacts with pore water) ranges from 0.3 to 3%. Fabryka-Martin et al. (1991) estimated fission-produced [129]I to be up to 1.7×10^6 atoms L^{-1} (0.12 µBq L^{-1}) in the water of the Milk River sandstone, in some cases amounting to up to 87% of the [129]I present.

Specific activities of [129]I reported in the literature were especially variable, confounded by marked differences before and after the peak of fallout, a few recent point sources of [129]I and perhaps the widespread use of stable I in foods and other applications. For example, Cornett et al. (1997b) suggested specific activities before the fallout were about 0.6 Bq (kg I)$^{-1}$ (notably higher than the estimates by Hou et al. (2009), Kekli et al. (2003) and Renaud et al. (2005)), whereas after fallout they were much higher at about 130 Bq (kg I)$^{-1}$ (in teeth, vegetation and soil). With its very long half-life and the enhanced modern releases, pre-bomb levels may have little relevance for the near or far future because the entire global biosphere inventory of I will eventually have a higher-than-natural [129]I specific activity.
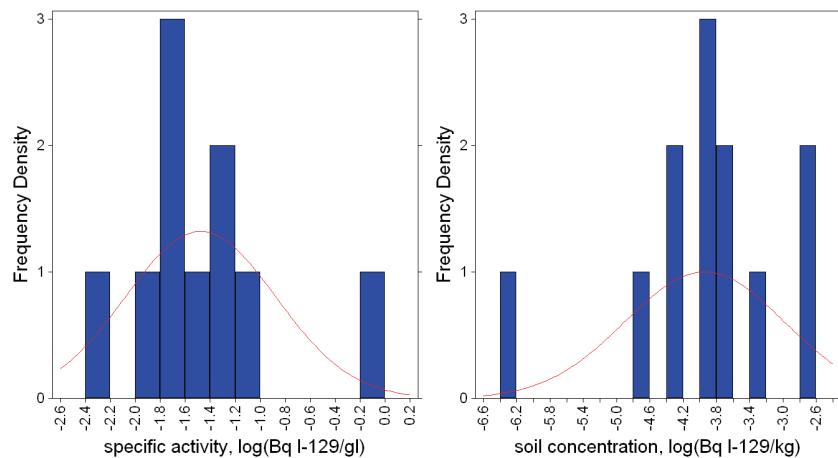
Figure 3-8: Frequency histograms of specific activities of [129]I in international soil samples (n = 10) and concentration of [129]I in international soils (n = 12). The red lines are the best-fit lognormal frequency curves.

For Canadian and international soil samples, the specific activities were:

Source	Canada n = 3	international n = 10
Minimum	1.8 Bq (kg I)$^{-1}$	4.7 Bq (kg I)$^{-1}$
Median	-	23 Bq (kg I)$^{-1}$
Maximum	43 Bq (kg I)$^{-1}$	800 Bq (kg I)$^{-1}$
Geometric mean (GM)	8.6 Bq (kg I)$^{-1}$	33 Bq (kg I)$^{-1}$
Geometric standard deviation (GSD)	3.7	4.0
Implied EI (GM x (GSD - 1))	23 Bq (kg I)$^{-1}$	

For Canadian organic and mineral soils and international soils, the concentrations were:

Source	Canada n = 5	international n = 12
Minimum	0.022 mBq kg^{-1}	0.00047 mBq kg^{-1}
Median	0.22 mBq kg^{-1}	0.14 mBq kg^{-1}
Maximum	0.70 mBq kg^{-1}	2.2 mBq kg^{-1}
Geometric mean (GM)	0.14 mBq kg^{-1}	0.11 mBq kg^{-1}
Geometric standard deviation (GSD)	4.1	9.1
Implied EI (GM x (GSD - 1))	0.43 mBq kg^{-1}	0.9 mBq kg^{-1}

Specific activities and concentrations of ^{129}I in water samples were also extremely variable (Figure 3-9).
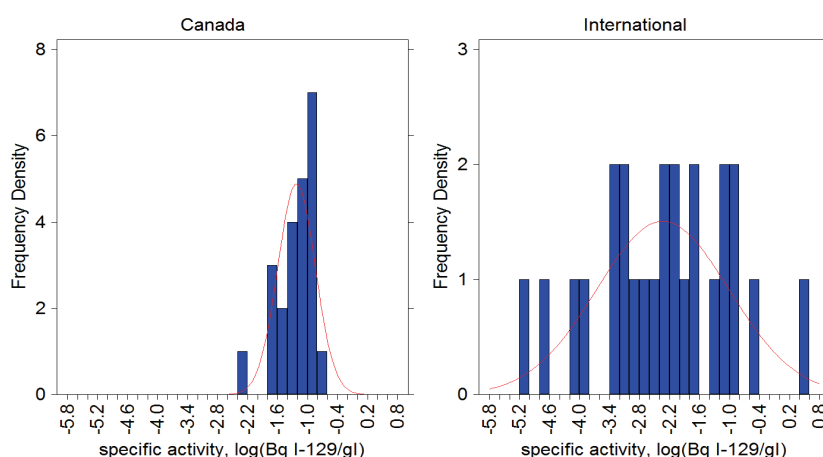
Figure 3-9: Frequency histograms of specific activities of ^{129}I in water in Canada (n = 23) and international (n = 25). The red lines are the best-fit lognormal frequency curves.

For the Canadian and international water samples, the specific activities were:

Source	Canada n = 23	international n = 25
Minimum	16 Bq (kg I)$^{-1}$	9.6x10^{-6} Bq (kg I)$^{-1}$
Median	93 Bq (kg I)$^{-1}$	5.1 Bq (kg I)$^{-1}$
Maximum	600 Bq (kg I)$^{-1}$	3000 Bq (kg I)$^{-1}$
Geometric mean (GM)	74 Bq (kg I)$^{-1}$	4.6 Bq (kg I)$^{-1}$
Geometric standard deviation (GSD)	2.2	21
Implied EI (GM x (GSD - 1))	90 Bq (kg I)$^{-1}$	90 Bq (kg I)$^{-1}$
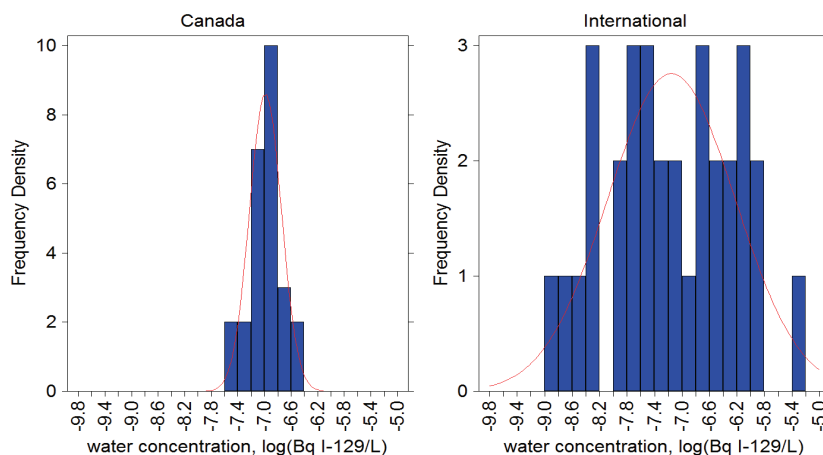
Figure 3-10: Frequency histograms of concentrations of ^{129}I in water in Canada (n = 26) and international (n = 32). The red lines are the best-fit lognormal frequency curves.

For the Canadian and international water samples, the concentrations were:

Source	Canada n = 26	international n = 32
Minimum	0.034 µBq L^{-1}	0.0013 µBq L^{-1}
Median	0.11 µBq L^{-1}	0.070 µBq L^{-1}
Maximum	0.28 µBq L^{-1}	5.7 µBq L^{-1}
Geometric mean (GM)	0.10 µBq L^{-1}	0.070 µBq L^{-1}
Geometric standard deviation (GSD)	1.7	8.4
Implied EI (GM x (GSD - 1))	0.07 µBq L^{-1}	0.52 µBq L^{-1}

Stable I concentrations in soils were reported by Sheppard et al. (1989), Rao and Fehn (1999), and (Sheppard et al. 2009a), together giving a GM of 1.6 mg kg^{-1} and variation of about 1.8-fold.

Rao and Fehn (1999) measured stable I in surface waters across North America, with a median of 0.2 µg L^{-1}. Data from Sheppard et al. (2009a) were higher, with a GM for lake waters on the Precambrian Shield of 1.2 µg L^{-1} and for drinking water (both well and surface waters) of 3.8 µg L^{-1}. The GSD values for these data were 1.5- to 2.4-fold, suggesting these concentrations differed significantly from the concentrations reported by Rao and Fehn (1999). The GM stable I concentration for 21 rivers and lakes sampled in 2010 (Sheppard and Sanipelli 2011) was 1.6 µg L^{-1}, with a GSD of 1.8. Using the GM specific activity in Canadian water samples of 74 Bq (kg I)$^{-1}$ (above), the concentrations of 1.2 to 1.6 µg ^{127}I L^{-1} imply 0.09 to 0.1 µBq L^{-1}, consistent with the observed activity concentrations.

3.8   CESIUM-137

Cesium-137 is a fission product, and apart from a small amount of natural spontaneous fission, the dominant sources of ^{137}Cs are nuclear reactors and fallout. Soil concentrations of ^{137}Cs are commonly measured: the analytical method with gamma spectroscopy is simple and ^{137}Cs is considered one of the major fingerprints of fallout and some current nuclear facilities. Although stable Cs is relatively abundant and does affect the sorption reactions of ^{137}Cs, the specific activity of ^{137}Cs is not considered useful to represent environmental concentrations because

stable Cs is largely of geological origin and ^{137}Cs is largely of atmospheric (fallout) origin, so there is no inherent value in the specific activity.

Almost all the ^{137}Cs present in the biosphere results from fallout and is relatively uniform in distribution, whereas the contribution from Chernobyl is much smaller except in a few specific locations in Europe. There is a latitudinal effect for ^{137}Cs: most is in the temperate latitudes of the northern hemisphere, consistent with the latitudes for many of the bomb tests. Barrie et al. (1992) showed 5-fold higher concentrations at 60-70°N compared to 80-90°N.
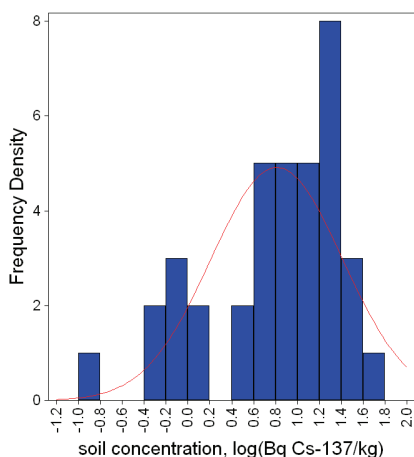
Figure 3-11: Frequency histogram of ^{137}Cs concentrations in soil (n = 37). The red line is the best-fit lognormal frequency curve.

The apparent bimodal frequency density (Figure 3-11) reflects that soil samples from the arctic and sandy soils tend to have an order of magnitude lower ^{137}Cs concentrations than do finer textured, temperate latitude soils. It is probable that this bimodal trend would not be apparent if data for a fuller distribution of soil textures had been available.

There were statistically significant differences among regions. The highest concentrations were in samples from Atlantic Canada (14 Bq kg^{-1}, n = 2), BC (11 Bq kg^{-1}, n = 2), the Precambrian Shield outside of Ontario (19 Bq kg^{-1}, n = 8) and western Canada (12 Bq kg^{-1}, n = 4). The lowest concentrations were in northern Canada (1.2 Bq kg^{-1}, n = 4). Southern Ontario had intermediate (4.9 Bq kg^{-1}, n = 16) concentrations.

For the 36 soil concentrations, the values were:

Minimum	0.15 Bq kg^{-1}
Median	10 Bq kg^{-1}
Maximum	60 Bq kg^{-1}
Geometric mean (GM)	6.5 Bq kg^{-1}
Geometric standard deviation (GSD)	4.0
Implied EI (GM x (GSD - 1))	20 Bq kg^{-1}

Water concentrations of ^{137}Cs, as with ^{90}Sr, are still being influenced by runoff of ^{137}Cs from watershed soils. At the same time, there is burial in sediment and downstream flushing. Tracy

and Prantl (1983) provided a two-phase model of the decrease in ^{137}Cs in the Great Lakes with time since the peak deposition in 1963. In Lake Superior, 70% of the ^{137}Cs diminished with a half-time of 0.53 a and 30% with a half-time of 5.5 a. In Lake Huron, 97.5% of the ^{137}Cs diminished with a half-time of 0.22 a and 2.5% with a half-time of 19 a. Most of the data were published in the early 1990's, so these functions would suggest a decrease of 5- to 10-fold from 1990 to 2010. However, this was not supported by recent data from AECL Whiteshell (2008) and AECL Chalk River (2008) where concentrations are consistent with the data from the 1990's. However, the AECL data are very near the detection limits, and are less reliable as a result.
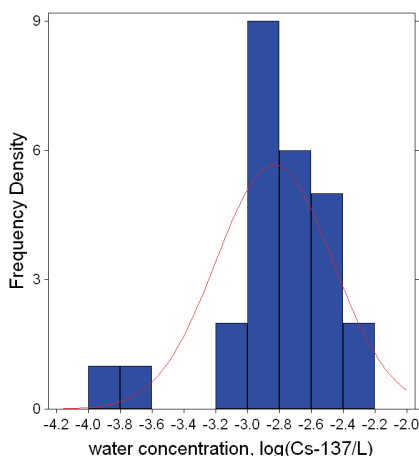
Figure 3-12: Frequency histogram of ^{137}Cs concentrations in water (n = 26). The red line is the best-fit lognormal frequency curve.

Although the frequency density plot for water concentrations appears bimodal (Figure 3-12), there is no apparent explanation for the exceptionally low values. Some variation in the data may result from different pre-concentration methods, which will change detection limits by up to an order of magnitude. The especially low reported concentrations may be cases where the detection limit was also low, and other laboratories may have reported higher concentrations using as a default the detection limit values.

For the 26 water concentrations, the values were:

Minimum	0.12 mBq L^{-1}
Median	1.6 mBq L^{-1}
Maximum	5 mBq L^{-1}
Geometric mean (GM)	1.5 mBq L^{-1}
Geometric standard deviation (GSD)	2.3
Implied EI (GM x (GSD - 1))	2.0 mBq L^{-1}

The differences among regions were not statistically significant, but there was a trend that the lower Great Lakes and St. Lawrence River had slightly lower concentrations (1 mBq L^{-1}, n = 13) compared to Lake Superior, the Ottawa River, the Precambrian Shield and north of 60°N (2 mBq L^{-1}, n = 13). This north/south trend is opposite that shown for soil samples, and may not be real. However, it may be the result of water balance and soil types: the northern soils

may be less retentive because of low pH, low clay contents and higher net water infiltration. This results in greater transfer of Cs to water bodies which may retain Cs in solution because of low pH and clay sediments.

3.9   BISMUTH-210

Bismuth-210 is in the ^{238}U decay series, and thus is a product of a primordial radionuclide. The half-life of ^{210}Bi is 5 d and it is assumed to be in secular equilibrium with its parent, ^{210}Pb. Indeed, many of the analyses reported for ^{210}Pb are in fact the results of detection of beta emissions from ^{210}Bi. Thus, the assumption of secular equilibrium is necessitated by the way the data were obtained. The background concentration and EI values for ^{210}Pb (and ^{210}Po) apply to ^{210}Bi. From the following section of this report dealing with ^{210}Pb, the GM soil concentration is 47 Bq kg^{-1} (EI of 110 Bq kg^{-1}) and the GM water concentration is 6.4 mBq L^{-1} (EI of 20 mBq L^{-1}).

3.10   LEAD-210

Concentrations of ^{210}Pb in soils occurs entirely because of the ^{238}U (4n + 2) decay series, but can arrive in the soil by at least two processes. One is the decay of chain radionuclides that were present in the soil parent materials, resulting in the ingrowth of ^{210}Pb. However, the ^{210}Pb may not be in secular equilibrium with soil ^{226}Ra and higher members of the chain because the intermediary ^{222}Rn (radon) is volatile. Thus, some ^{222}Rn may escape the soil resulting in disequilibrium between ^{210}Pb and ^{226}Ra. The second process for generation of ^{210}Pb in soil is related to radon: as radon decays in the atmosphere, insoluble ^{210}Pb is formed, it attaches to particles and falls on the soil surface. The soil can accumulate ^{210}Pb beyond what is expected from ingrowth if the radon in the atmosphere comes from sources other than the surface soil. An example would be radon emitted from lakes or deep soils that is then transferred to the top soil. Despite these complications, soil ^{210}Pb concentrations are not especially variable.
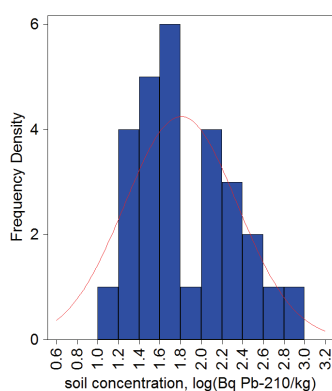
Figure 3-13: Frequency histogram of ^{210}Pb concentrations in mineral soil (n = 25). The red line is the best-fit lognormal frequency curve.

For the 25 mineral soil concentrations, the values were:

Minimum	2.5 Bq kg^{-1}
Median	50 Bq kg^{-1}
Maximum	800 Bq kg^{-1}
Geometric mean (GM)	49 Bq kg^{-1}
Geometric standard deviation (GSD)	3.2
Implied EI (GM x (GSD - 1))	110 Bq kg^{-1}

There were data for 4 organic soils, with a GM of 310 Bq kg^{-1} and GSD of 1.3-fold. Given that the bulk density of an organic soil may be about one-tenth that of a mineral soil, the GM of 310 Bq kg^{-1} for the organic soils is consistent with that of the mineral soils if both were expressed per unit volume or per unit landscape surface area. Given the atmospheric source of much of the ^{210}Pb, a similar value per unit landscape surface area might be expected regardless of soil type.

There were no statistically significant differences among regions in soil ^{210}Pb concentrations.
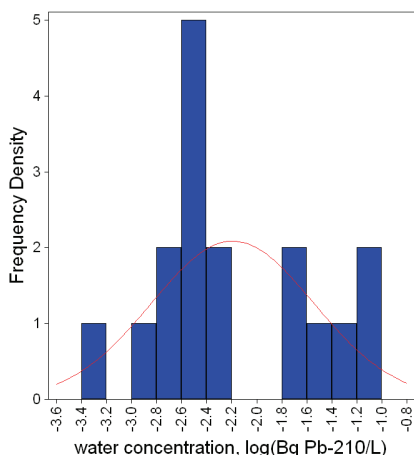
Figure 3-14: Frequency histogram of ^{210}Pb concentrations in water (n = 17), excluding all values recorded as at the corresponding detection limits. The red line is the best-fit lognormal frequency curve.

For the 17 water concentrations above their detection limits, the values were:

Minimum	0.5 mBq L^{-1}
Median	3.6 mBq L^{-1}
Maximum	86 mBq L^{-1}
Geometric mean (GM)	6.4 mBq L^{-1}
Geometric standard deviation (GSD)	4.5
Implied EI (GM x (GSD - 1))	20 mBq L^{-1}

Although there were no statistically significant differences among regions in water ^{210}Pb concentrations, the probability level for differences was P = 0.09[12]. Lake Huron appeared to be

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[12] Statistical significance is usually assigned at P < 0.05, so this level is 'nearly' significant.

low (0.5 mBq L^{-1}, n = 1), the Ottawa River, northern Ontario and eastern Canada were intermediate (4 mBq L^{-1}, n = 9), and the Precambrian Shield outside of Ontario, western Canada and north of 60°N were highest (30 mBq L^{-1}, n = 7). These differences might be attributable to the regional average amount of overburden between the U-bearing rocks and the water bodies. The overburden would retard radon movement and retain Pb.

3.11   POLONIUM-210

Polonium-210 is also in the ^{238}U decay series, and thus is a product of a primordial radionuclide. Because the half-life of ^{210}Po is only 138 d, it is often in secular equilibrium with its parent ^{210}Pb. Ten values for both soil and water were found in the literature and are summarized here.
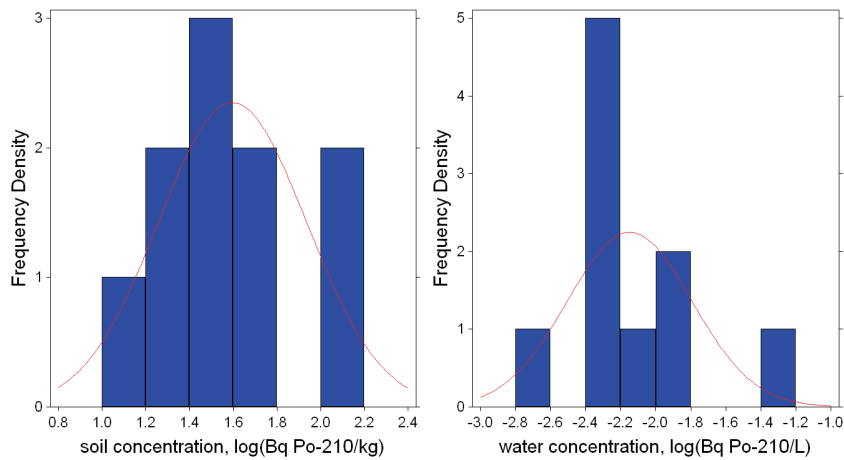
Figure 3-15: Frequency histograms of concentrations of ^{210}Po in soil (n = 10) and in water (n = 10). The red lines are the best-fit lognormal frequency curves.

For the 10 soil concentrations, the values were:

Minimum	14 Bq kg^{-1}
Median	35 Bq kg^{-1}
Maximum	150 Bq kg^{-1}
Geometric mean (GM)	40 Bq kg^{-1}
Geometric standard deviation (GSD)	2.2
Implied EI (GM x (GSD - 1))	48 Bq kg^{-1}

For the 10 water concentrations above their detection limits, the values were:

Minimum	2.5 mBq L^{-1}
Median	5.5 mBq L^{-1}
Maximum	49 mBq L^{-1}
Geometric mean (GM)	7.1 mBq L^{-1}
Geometric standard deviation (GSD)	2.3
Implied EI (GM x (GSD - 1))	9.2 mBq L^{-1}

As expected, the GM concentrations in soil and water for ^{210}Po were nearly the same as in the previous section for ^{210}Pb. In both cases, the GSD was larger for ^{210}Pb than ^{210}Po, but there is no obvious reason why this might be the result of physical or chemical processes. One could argue that the data for ^{210}Pb and ^{210}Po be combined, but this changes the meaning of the GSD from a measure of variation from study to study and site to site to a measure of variation from analytical method to method.

3.12   RADON-222 and RADIUM-223,224

Radon is an important radionuclide for two primary reasons. In the decay series, it often disrupts secular equilibrium because as a gas it can migrate away from the site where it was formed. Although this migration is most notable in the atmosphere, it also occurs in unsaturated porous media. Radon is quite soluble in water, so its migration in water-filled pores is not as great. Concentrations of ^{222}Rn are not useful for dose prediction per se, but the emission factors based on soil and water ^{226}Ra concentration are important. Sheppard et al. (2006) reviewed radon emission factors, and so no further review is done here.

Radium-223 is a member of the ^{235}U decay series, and because it has a short half-life (11 days) it is usually considered to be in secular equilibrium with its parent ^{227}Ac (half-life 22 a) and grandparent ^{231}Pa. There are few if any data for ^{223}Ra in environmental media. Amiro (1992, 1993) reported that ^{231}Pa (half-life 3.28 x 10^4 a) was in secular equilibrium with ^{235}U in the lithosphere, and he assumed this applied to soils. In contrast, he assumed that ^{231}Pa was depleted 500-fold relative to ^{235}U in aquatic systems, based on data for marine samples. In turn, there are few data for ^{235}U and it is often assumed to be 0.72% by mass of ^{238}U. Using these assumptions, the background concentration of ^{223}Ra in soil, based on ^{238}U as given in a later section of this report, is 1 Bq kg^{-1} (EI of 0.8 Bq kg^{-1}). For water, including the 500-fold decrease, the values are 0.4 µBq L^{-1} (EI of 1 µBq L^{-1}).

Radium-224 is a member of the ^{232}Th (4n) decay series and has a short half-life (3.6 days). Thus it is reasonably assumed to be in secular equilibrium with its parent ^{228}Th (half-life 1.9 a), grandparent ^{228}Ac (half-life 6 hrs) and great grandparent ^{228}Ra (half-life 5.75 a). Amiro (1992, 1993) assumed secular equilibrium in soils for all these three nuclides with their great-great grandparent ^{232}Th, but assumed a 20-fold accumulation of ^{228}Ra over ^{232}Th in water, again based on data for marine samples. As a result, data for ^{228}Ra are potentially important, but data for ^{224}Ra will be sparse and not needed. Using these assumptions, the background concentration of ^{224}Ra in soil, based on ^{232}Th as given in a later section of this report, is 23 Bq kg^{-1} (EI of 25 Bq kg^{-1}). For water, including the 20-fold increase, the values are 0.015 Bq L^{-1} (EI of 0.036 Bq L^{-1}).

3.13   RADIUM-226

Radium-226 is a progeny of the ^{238}U decay series. There is interest in measuring ^{226}Ra largely because it is the parent of radon, and radon progeny are both major dose contributors and important tracers of environmental processes. There are at least 3 common methods to measure ^{226}Ra concentrations, including alpha spectroscopy, gamma spectroscopy and measurement of radon after ingrowth in sealed containers.

Soil concentrations are not especially variable (Figure 3-16), but water concentrations had a range of 1600-fold and a GSD of 6.3. Some of this variation may be related to variation in the solubility of the parent radionuclides, especially ^{230}Th which can vary substantially in solubility because of the presence or absence of natural organic ligands.
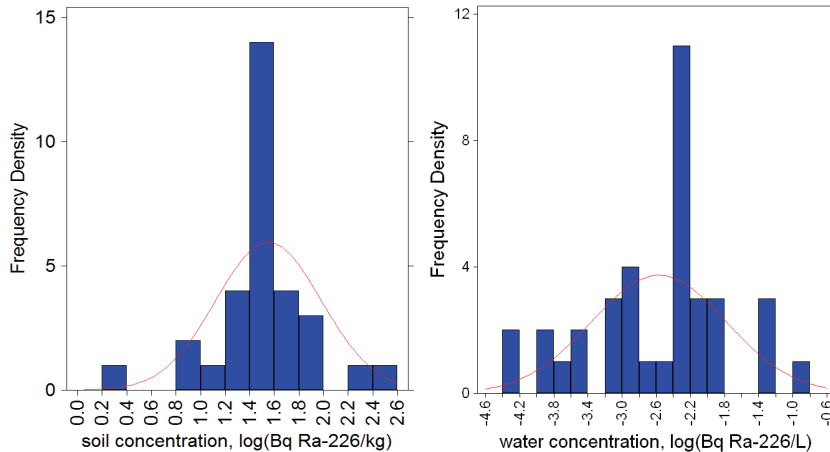
Figure 3-16: Frequency histograms of concentrations of ^{226}Ra in mineral soil (n = 27) and in water (n = 36). The red lines are the best-fit lognormal frequency curves.

For the 27 mineral soil concentrations, the values were:

Minimum	2.5 Bq kg^{-1}
Median	30 Bq kg^{-1}
Maximum	170 Bq kg^{-1}
Geometric mean (GM)	29 Bq kg^{-1}
Geometric standard deviation (GSD)	2.2
Implied EI (GM x (GSD - 1))	35 Bq kg^{-1}

There were data for 3 organic soils, with a GM of 52 Bq kg^{-1}, and in addition 2 other organic soils near U mineralizations with a GM of 410 Bq kg^{-1}.

There were no statistically significant differences in soil concentrations among regions.

For the 36 water concentrations, the values were:

Minimum	0.06 mBq L^{-1}
Median	5.0 mBq L^{-1}
Maximum	100 mBq L^{-1}
Geometric mean (GM)	2.7 mBq L^{-1}
Geometric standard deviation (GSD)	6.3
Implied EI (GM x (GSD - 1))	14 mBq L^{-1}

There were statistically significant differences among regions, in general waters from the Precambrian Shield, western Canada and north of 60°N had higher concentrations (7 mBq L^{-1}, n = 22) compared to the rest of Canada (0.7 mBq L^{-1}, n = 14). As with ^{210}Pb, this may result

because the watersheds in the north tend to have less overburden, less clay and lower pH than in the south, all of which would facilitate transfer of ^{226}Ra to the water bodies.

3.14   ACTINIUM-227 and THORIUM-227

Actinium-227 (half-life 21.77 a) and ^{227}Th (half-life 18.72 d) are assumed to be in secular equilibrium with their parent ^{231}Pa (and with their progeny ^{223}Ra) in soil. Amiro (1992, 1993) assumed that activity concentrations of ^{231}Pa were 500-fold lower than for the grandparent ^{235}U in water, based on marine studies. In absence of other data, and in recognition that low values for EI are conservative, the same assumption is made here. Using these assumptions, the background concentration of both ^{227}Ac and ^{227}Th soil, based on ^{238}U as given in a later section of this report, is 1 Bq kg^{-1} (EI of 0.8 Bq kg^{-1}). For water, including the 500-fold decrease, the values are 0.4 µBq L^{-1} (EI of 1 µBq L^{-1}).

3.15   RADIUM-228

Radium-228 is a progeny of the ^{232}Th decay series. With a half-life of 5.8 a, ^{228}Ra is usually in secular equilibrium with its parent ^{232}Th, especially in soil. Tracy and Prantl (1985) estimated ^{228}Ra based on this assumption. Sheppard et al. (2008) and Sheppard and Sanipelli (2011) measured ^{228}Ra concentrations in soil of about 40 Bq kg^{-1}, and these were approximately equal to the concentrations they reported for ^{232}Th. Thus the background and EI values for ^{228}Ra can be based on that for ^{232}Th, as done by Amiro (1992, 1993). Note that Amiro assumed 20-fold higher concentrations of ^{228}Ra relative to ^{232}Th in water, based on marine water data as described above; however, there is now reliable data for ^{228}Ra in fresh water, and they do not support the 20-fold factor.

For the 7 water concentrations, the values were:

Minimum	0.08 mBq L^{-1}
Median	0.25 mBq L^{-1}
Maximum	0.94 mBq L^{-1}
Geometric mean (GM)	0.29 mBq L^{-1}
Geometric standard deviation (GSD)	2.2
Implied EI (GM x (GSD - 1))	0.35 mBq L^{-1}

This GM of 0.29 mBq L^{-1} is much more consistent with direct secular equilibrium with ^{232}Th, where the GM concentration, given in a later section of this report, was 0.73 mBq L^{-1}.

3.16   THORIUM-228

Thorium-228 is a progeny of the ^{232}Th decay series. The half-life of ^{228}Th is 1.9 a and so it is usually in equilibrium with its parent ^{228}Ra, which in turn is in equilibrium with ^{232}Th, at least in soils (Amiro (1992, 1993) proposed 20-fold higher ^{228}Th than ^{232}Th concentrations in water) . Sheppard et al. (2008) and Sheppard and Sanipelli (2011) measured ^{228}Th concentrations in soil of about 40 Bq kg^{-1}, and these were approximately equal to the concentrations they reported for ^{232}Th and ^{228}Ra. Brunskill and Wilkinson (1987) reported ^{228}Th concentrations of 36 Bq kg^{-1} in soils where they reported ^{232}Th concentrations of 22 Bq kg^{-1}, perhaps close enough to support the assumption of secular equilibrium. Assuming secular equilibrium, the

background concentration of ^{228}Th in soil, based on ^{232}Th as given in a later section of this report, is 23 Bq kg^{-1} (EI of 25 Bq kg^{-1}).

Lupien and Grondin (1984) provided the necessary ^{228}Th and ^{228}Ra data needed to evaluate secular equilibrium in freshwater. Their concentrations of ^{228}Th were 2.8- to 6.4-fold (average 3.5-fold) higher than for ^{228}Ra, somewhat less than the 20-fold ratio assumed by Amiro (1992, 1993) but already questioned in discussion of ^{228}Ra in the above section of this report. For water, assuming the 20-fold increase of the activity concentrations of ^{232}Th, the values are 0.015 Bq L^{-1} (EI of 0.036 Bq L^{-1}). However, there were data for ^{228}Th in water.
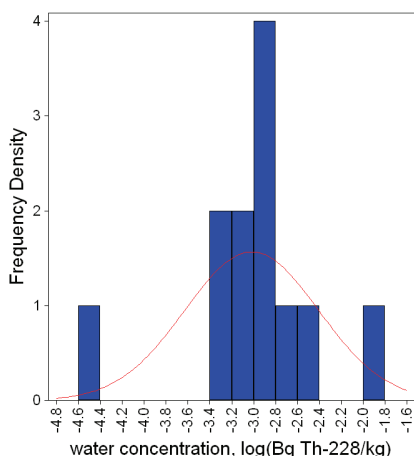
Figure 3-17: Frequency histogram of concentrations of ^{228}Th in water (n = 12). The red line is the best-fit lognormal frequency curves.

For the 12 water concentrations, the values were:

Minimum	0.028 mBq L^{-1}
Median	0.12 mBq L^{-1}
Maximum	1.2 mBq L^{-1}
Geometric mean (GM)	0.96 mBq L^{-1}
Geometric standard deviation (GSD)	4.1
Implied EI (GM x (GSD - 1))	3.0 mBq L^{-1}

This GM of 0.96 mBq L^{-1} is much more consistent with direct secular equilibrium with ^{232}Th, where the GM concentration, given in a later section of this report, was 0.73 mBq L^{-1}. This is further evidence that the 20—fold upward adjustment recommended by Amiro (1992, 1993) based on marine systems does not apply to fresh water. There are sufficient measured data for ^{228}Th to consider them reliable.

There are statistically significant differences among regions. In general, the Great Lakes and eastern Canada had lower concentrations (0.3 mBq L^{-1}, n = 7) compared to the Ottawa River and the Precambrian Shield (2 mBq L^{-1}, n = 5).

3.17   THORIUM-230

Thorium-230 (sometimes referred to as Ionium) is in the ^{238}U (4n + 2) decay series, but between long lived ^{234}U and ^{226}Ra, so is not expected to be found at secular equilibrium in the environment. None the less, ^{230}Th is not commonly reported.

Figure 3-18: Frequency histograms of concentrations of ^{230}Th in soil (n = 5) and in water (n = 5). The red lines are the best-fit lognormal frequency curves.

For the 5 soil concentrations, the values were:

Minimum	9 Bq kg^{-1}
Median	20 Bq kg^{-1}
Maximum	40 Bq kg^{-1}
Geometric mean (GM)	19 Bq kg^{-1}
Geometric standard deviation (GSD)	1.9
Implied EI (GM x (GSD - 1))	17 Bq kg^{-1}

For the 5 water concentrations above their detection limits, the values were:

Minimum	1.7 mBq L^{-1}
Median	4.9 mBq L^{-1}
Maximum	10 mBq L^{-1}
Geometric mean (GM)	1.9 mBq L^{-1}
Geometric standard deviation (GSD)	7.4
Implied EI (GM x (GSD - 1))	12 mBq L^{-1}

3.18   PROTACTINIUM-231

Protactinium-231 is a progeny of the ^{235}U decay series, and so is primordial. There were very few data for ^{231}Pa. Osburn (1965) reported ^{231}Pa to be in secular equilibrium in soil with ^{235}U, but had an error in units for the concentration reported. The corrected value was 3.9 Bq kg^{-1}. CBCL (1985) reported concentrations at an anomalous site, the lowest concentration was

120 Bq kg^{-1}, but this is still probably elevated. They reported a ^{235}U/^{231}Pa activity ratio of 83, but this was in a U 'roll front', where because of redox gradients U was especially mobile, and disequilibrium might be expected. Amiro (1992, 1993) assumed that activity concentrations of ^{231}Pa were 500-fold lower than for the grandparent ^{235}U in water, based on marine studies. In absence of other data, and in recognition that low values for EI are conservative, the same assumption is made here. However, there are few data for ^{235}U and it is often assumed to be 0.72% by mass of ^{238}U. Using these assumptions, the background concentration of ^{231}Pa in soil, based on ^{238}U as given in a later section of this report, is 1 Bq kg^{-1} (EI of 0.8 Bq kg^{-1}). For water, including the 500-fold decrease, the values are 0.4 µBq L^{-1} (EI of 1 µBq L^{-1}).

3.19   THORIUM-231

Thorium-231 has a half-life of 25 hrs, and so is assumed to be in secular equilibrium with its parent ^{235}U in both soil and water (the 500-fold decrease proposed by Amiro (1992, 1993) does not apply to ^{231}Th). There are few data for ^{235}U and it is often assumed to be 0.72% by mass of ^{238}U. Using these assumptions, the background concentration of ^{231}Th in soil, based on ^{238}U as given in a later section of this report, is 1 Bq kg^{-1} (EI of 0.8 Bq kg^{-1}). For water, the values are 0.17 mBq L^{-1} (EI of 0.45 mBq L^{-1}).

3.20   THORIUM-232

As the start of a primordial decay series and with a very long half-life (1.4 x 10^{10} a), ^{232}Th dominates the mass of Th in the environment. Thus it is appropriate to summarize the data both as mass concentration and activity concentration (they should differ by a constant conversion). For concentrations in soil, the values could be equally well described as normally or lognormally distributed, and both frequency distributions are shown in Figure 3-19. The EI values are computed from the GM and GSD to be consistent with other radionuclides.
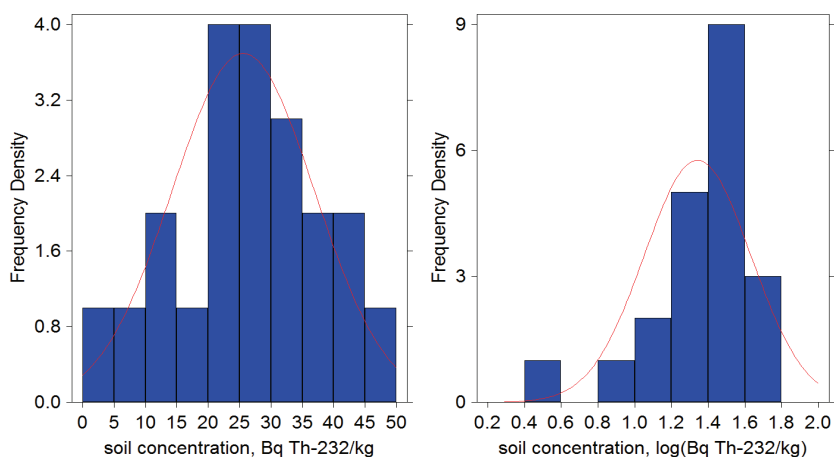
Figure 3-19: Frequency histograms of ^{232}Th activity concentrations in soil (n = 21). The red lines are the best-fit normal/lognormal frequency curves.

For the 21 soil concentrations, the values were:

Minimum	2.7 Bq kg^{-1}	0.7 mg kg^{-1}
Median	27 Bq kg^{-1}	6.6 mg kg^{-1}
Maximum	45 Bq kg^{-1}	11 mg kg^{-1}
Arithmetic mean	26 Bq kg^{-1}	6.3 mg kg^{-1}
Geometric mean (GM)	22 Bq kg^{-1}	5.4 mg kg^{-1}
Geometric standard deviation (GSD)	2.0	1.9
Implied EI (GM x (GSD - 1))	22 Bq kg^{-1}	4.9 mg kg^{-1}

There were no statistically significant differences in soil concentrations among regions. Maps of ^{232}Th concentrations across Canada are shown in Appendix B.
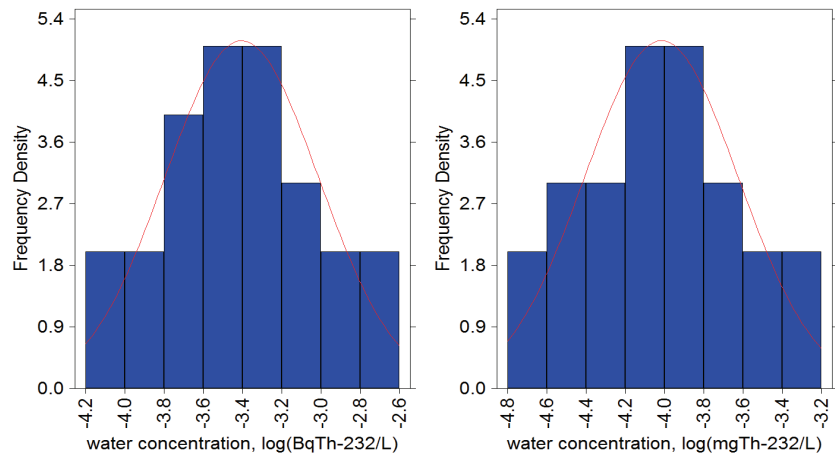
Figure 3-20: Frequency histogram of ^{232}Th activity concentrations and mass concentrations in water (n = 25). The red line is the best-fit lognormal frequency curves.

For the 25 water concentrations, the values were:

Minimum	0.082 mBq L^{-1}	0.020 µg L^{-1}
Median	0.36 mBq L^{-1}	0.088 µg L^{-1}
Maximum	2.2 mBq L^{-1}	0.54 µg L^{-1}
Geometric mean (GM)	0.39 mBq L^{-1}	0.096 µg L^{-1}
Geometric standard deviation (GSD)	2.5	2.5
Implied EI (GM x (GSD - 1))	0.59 mBq L^{-1}	0.14 µg L^{-1}

There were no statistically significant differences in water concentrations among regions.

3.21   THORIUM-234

Thorium-234 has a half-life of 24 d, and so is assumed to be in secular equilibrium with its parent ^{238}U. With this assumption, the background concentration of ^{234}Th in soil, based on ^{238}U as given in a later section of this report, is 24 Bq kg^{-1} (EI of 19 Bq kg^{-1}). For water, the values are 3.9 mBq L^{-1} (EI of 0.01 Bq L^{-1}).

3.22   URANIUM-234

Uranium-234 (half-life 2.4 x 10^5 a) is a decay product of ^{238}U (half-life 4.5 x 10^9 a). For natural U (^{nat}U), ^{234}U is present at 0.0054% atom ratio relative to ^{238}U at 99.274% and ^{235}U at 0.720%. Although the specific activity of ^{234}U is much higher than that of ^{238}U, this is counterbalanced by the atom abundance ratios so that they contribute nearly equal amounts to the specific activity of ^{nat}U. Thus, per unit mass of U, the total activity from all U isotopes is about double that of the ^{238}U alone. There is an alpha decay between ^{238}U and ^{234}U, so that alpha recoil could potentially mobilize ^{234}U relative to ^{238}U. In soils, the ^{234}U/^{238}U activity ratio was reported as 0.92 by CBCL (1985) and 1.05 by Brunskill and Wilkinson (1987). In surface waters, the ^{234}U/^{238}U activity ratio was reported as 1.08 by Ivanovich et al. (1991), 1.15 by Kronfeld et al. (2004) and 1.20 by Brunskill and Wilkinson (1987). In shallow well waters (drinking water), Gascoyne (1989) measured ^{234}U/^{238}U activity ratios of 2.6. These atom ratio data suggest that secular equilibrium may be expected in soils but that, perhaps because of alpha recoil, there is enhanced solubility and hence concentration of ^{234}U in water.

Brunskill and Wilkinson (1987) reported 21 Bq kg^{-1} in soil, with a GSD of about 2.2, implying an EI of 25 Bq kg^{-1}. This is very comparable to the GM of 24 Bq kg^{-1} with a GSD of 1.8 yielding an EI of 19 Bq kg^{-1} found for ^{238}U (in later sections of this report). Amiro (1992, 1993) reported a background activity concentration in soil (equal to that of ^{238}U) of 12 Bq kg^{-1}, a GSD of 3.16 and subsequently an EI of 26 Bq kg^{-1}.

Brunskill and Wilkinson (1987), Ivanovich et al. (1991) and Kronfeld et al. (2004) reported concentrations in surface waters of 3.6, 14 and 7.6 mBq L^{-1}, implying a GM of 7.3 mBq L^{-1}, a GSD of 1.7 and an EI of 5.1 mBq L^{-1}. This is also very comparable to the GM of 3.9 mBq L^{-1} with a GSD of 3.6 yielding an EI of 10 mBq kg^{-1} for ^{238}U.

3.23   URANIUM-235

As described above, ^{nat}U is assumed to include ^{235}U at an atom ratio of 0.72%. Lupien and Grondin (1984) measured both ^{235}U and ^{238}U, and their data indicate an atom ratio or 0.66%, which given analytical uncertainties is consistent with the standard value of 0.72%. CBCL (1985) indicated an atom ratio in soil of about 0.5%.

Waller and Cole (1999) and Sheppard and Sanipelli (2011) reported concentrations in 6 mineral soils with a GM of 0.79 Bq kg^{-1} and GSD of 1.6-fold, suggesting an EI of 0.5 Bq kg^{-1}. Sheppard and Sanipelli (2011) also reported a concentration of 460 Bq kg^{-1} in an organic soil near a known low-grade U mineralization. Assuming the atom ratio with ^{238}U of 0.72%, the implied background and EI concentrations for ^{235}U based on ^{238}U are 1 Bq kg^{-1} and 0.8 Bq kg^{-1}, quite comparable to the values of Waller and Cole (1999).

Lupien and Grondin (1984) measured ^{235}U in surface waters, resulting in a GM of 0.051 mBq L^{-1}, a GSD of 2.7 and thus an EI of 0.087 mBq L^{-1}. Assuming the atom ratio with ^{238}U of 0.72%, the implied background and EI concentrations for ^{235}U based on ^{238}U are 0.17 mBq L^{-1} and 0.45 mBq L^{-1}, within about 5-fold of the values from Lupien and Grondin (1984).
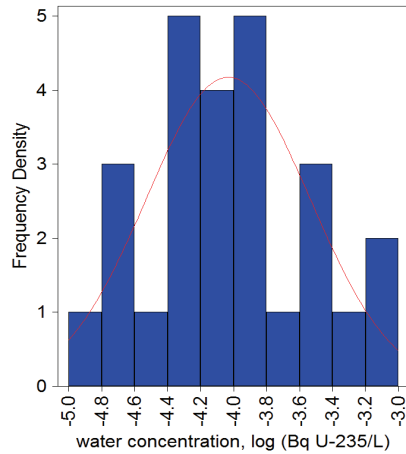
Figure 3-21: Frequency histogram of concentrations of ^{235}U in water (n = 26). The red line is the best-fit lognormal frequency curves.

For the 26 water concentrations, the values were:

Minimum	0.010 mBq L^{-1}
Median	0.076 mBq L^{-1}
Maximum	0.82 mBq L^{-1}
Geometric mean (GM)	0.093 mBq L^{-1}
Geometric standard deviation (GSD)	3.1
Implied EI (GM x (GSD - 1))	0.20 mBq L^{-1}

There were no statistically significant differences in water concentrations among regions.

3.24   URANIUM-238

As described above, by mass ^{238}U and ^{nat}U are essentially identical, but the specific activity of ^{238}U is 12.4 MBq (kg U)$^{-1}$ whereas for ^{nat}U it is 25.0 MBq (kg U)$^{-1}$ consisting of 12.4 MBq (kg U)$^{-1}$ from ^{238}U, 12.2 MBq (kg U)$^{-1}$ from ^{234}U and 0.566 MBq (kg U)$^{-1}$ from ^{235}U (Veska and Eaton 1991). Note that Ahier and Tracy (1997) used a different atom ratio of ^{235}U for emissions from a fuel processing facility, giving 28.4 MBq (kg U)$^{-1}$ for ^{nat}U in the environment but assumed to come from that facility.
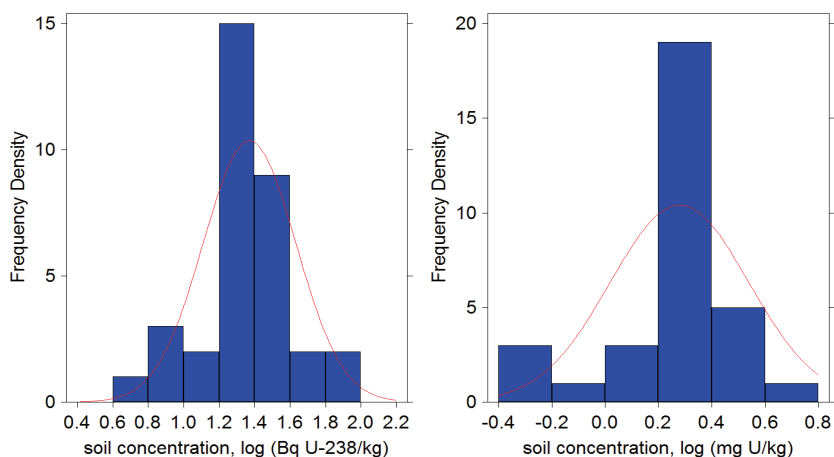
Figure 3-22: Frequency histograms of ^{238}U activity concentrations and mass concentrations in mineral soil (n = 34). The red lines are the best-fit lognormal frequency curves.

For the 34 mineral soil concentrations, the values expressed as activity concentration of ^{238}U, activity concentration of ^{nat}U and mass concentration were:

	^{238}U	^{nat}U	U
Minimum	5 Bq kg^{-1}	10 Bq kg^{-1}	0.4 mg kg^{-1}
Median	25 Bq kg^{-1}	50 Bq kg^{-1}	2.0 mg kg^{-1}
Maximum	86 Bq kg^{-1}	170 Bq kg^{-1}	7.0 mg kg^{-1}
Geometric mean (GM)	23 Bq kg^{-1}	49 Bq kg^{-1}	1.9 mg kg^{-1}
Geometric standard deviation (GSD)	1.8	1.8	1.8
Implied EI (GM x (GSD - 1))	18 Bq kg^{-1}	39 Bq kg^{-1}	1.5 mg kg^{-1}

Note that an organic soil near a low-grade U mineralization at Black Lake, Manitoba, had a concentration of 9700 Bq kg^{-1} (780 mg kg^{-1}). This number is high because of both the U mineralisation and the low bulk density of the peat. Five other organic soils had concentrations in the range of 12 to 61 Bq kg^{-1}, more consistent with the mineral soils represented in Figure 3-22. Clearly, there are U hot spots related to localized mineralization.

There were no statistically significant differences in soil concentrations among regions for the data compiled. However, gamma survey maps do show trends, and maps of ^{238}U concentrations across Canada are shown in Appendix B.
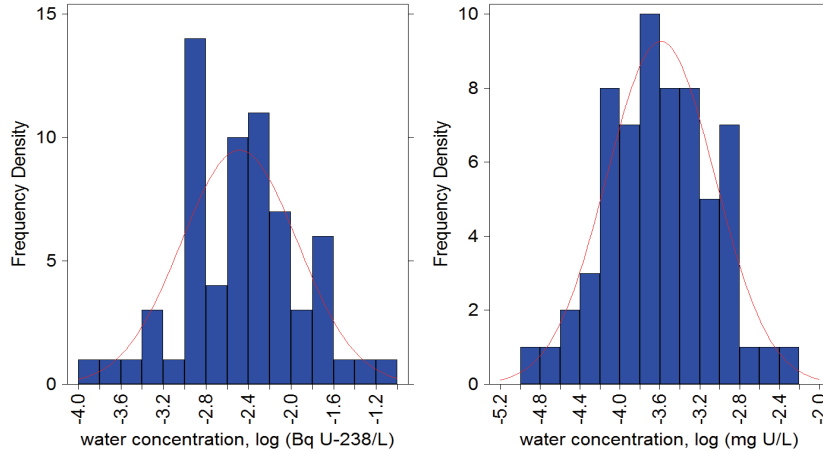
Figure 3-23: Frequency histogram of ^{238}U activity concentrations and mass concentrations in water (n = 63). The red line is the best-fit lognormal frequency curves.

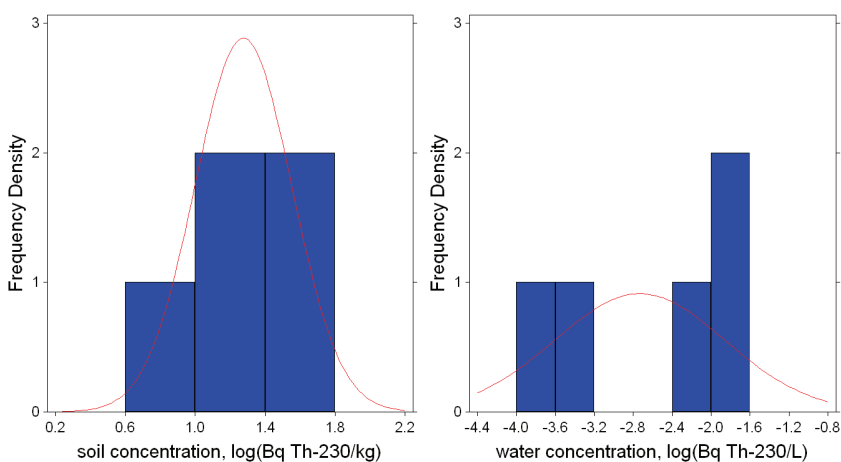For the 63 water concentrations, the values expressed as activity concentration of ^{238}U, activity concentration of ^{nat}U and mass concentration were:

	^{238}U	^{nat}U	U
Minimum	0.15 mBq L^{-1}	0.30 mBq L^{-1}	0.012 µg L^{-1}
Median	3.1 mBq L^{-1}	6.3 mBq L^{-1}	0.25 µg L^{-1}
Maximum	64 mBq L^{-1}	130 mBq L^{-1}	5.2 µg L^{-1}
Geometric mean (GM)	3.3 mBq L^{-1}	6.5 mBq L^{-1}	0.26 µg L^{-1}
Geometric standard deviation (GSD)	3.5	3.5	3.5
Implied EI (GM x (GSD - 1))	8.3 mBq L^{-1}	16 mBq L^{-1}	0.65 µg L^{-1}

There were no statistically significant differences in water concentrations among regions. However, there was a slight increasing trend downstream through the Great Lakes, from Lake Superior (1 mBq L^{-1}, n = 1), to Lakes Michigan and Huron (4 mBq L^{-1}, n = 4) and Lakes Erie and Ontario (6 mBq L^{-1}, n = 6).

4. SUMMARY AND CONCLUSIONS

The amount of data for concentrations in the environment is quite variable among radionuclides. There is undoubtedly more data for radionuclides that are easy to measure, and much fewer for the others. Some of the rarely measured, such as ^{14}C, ^{36}Cl and ^{129}I require expensive accelerator mass spectroscopy methods to detect environmental concentrations, and for these the atom ratios with their stable isotopes are especially useful. Others of the rarely measured are commonly assumed to be in secular equilibrium with more easily measured radionuclides.

Table 4.1 is a summary of the background concentrations and derived EI values, along with foot notes to explain assumptions as needed. Some of these values differ markedly from those proposed by Amiro (1992, 1993). This is largely the result of more recent data.

The concept of setting the EI as one (arithmetic) standard deviation [EI = SD], or the log distribution equivalent [EI = GM ·(GSD – 1)] yields some interesting results. For radionuclides that are normally distributed and for others where the spread of data is not too extreme, the EI is less than or similar in value to the (arithmetic or geometric) mean background concentration. However, when the data are lognormally distributed and the GSD exceeds 2, then the EI is larger, and sometimes almost tenfold larger, than the GM. Regardless of whether the data are normally or lognormally distributed, one SD or one GSD above the mean or GM represents a consistent probability level – these levels would not be statistically different from the mean or GM despite that they may be several fold higher. It would be very difficult to attribute an ecological impact to such a low relative increase in concentration above background.

Table 4-1: Summary of background and environmental increment values. Note that although most values are concentrations, specific activities are also given for ^{3}H, ^{14}C, ^{36}Cl and ^{129}I.

Radionuclide	Soil background (Bq kg^{-1})	Soil environmental increment (Bq kg^{-1})	Water background (Bq L^{-1})	Water environmental increment (Bq L^{-1})
^{3}H	0.04	---	3.2 37 Bq (kg H)$^{-1}$	4.2
^{14}C	3 239 Bq (kg C)$^{-1}$	5 17 Bq (kg C)$^{-1}$	0.001 239 Bq (kg C)$^{-1}$	0.0005 17 Bq (kg C)$^{-1}$
^{36}Cl	0.0002 1.0 Bq (kg Cl)$^{-1}$	0.0001 5.6 Bq (kg Cl)$^{-1}$	$5.1 \cdot 10^{-6}$ 0.96 Bq (kg Cl)$^{-1}$	$18 \cdot 10^{-6}$ 5.0 Bq (kg Cl)$^{-1}$
^{40}K	430	210	0.033	0.030
^{87}Rb	25	12	$0.26 \cdot 10^{-3}$	$0.62 \cdot 10^{-3}$
^{90}Sr	2.9	7.3	0.015	0.012
^{129}I	$0.14 \cdot 10^{-3}$ 8.6 Bq (kg I)$^{-1}$	$0.43 \cdot 10^{-3}$ 23 Bq (kg I)$^{-1}$	$0.10 \cdot 10^{-6}$ 74 Bq (kg I)$^{-1}$	$0.07 \cdot 10^{-6}$ 90 Bq (kg I)$^{-1}$
^{137}Cs	6.5	20	$1.5 \cdot 10^{-3}$	$2.0 \cdot 10^{-3}$
^{210}Bi	(49)[a]	(110)[a]	$(6.4 \cdot 10^{-3})$[a]	(0.020)[a]
^{210}Pb	49	110	$6.4 \cdot 10^{-3}$	0.020
^{210}Po	40 (49)[a]	48 (110)[a]	$7.1 \cdot 10^{-3}$ $(6.4 \cdot 10^{-3})$[a]	$9.2 \cdot 10^{-3}$ (0.020)[a]
^{222}Rn	Not relevant	not relevant	not relevant	not relevant
^{223}Ra	(1)[b]	(0.8)[b]	$(0.2 \cdot 10^{-6})$[c]	$(0.4 \cdot 10^{-6})$[c]
^{224}Ra	(22)[d]	(22)[d]	$(7.8 \cdot 10^{-3})$[e]	(0.012)[e]
^{226}Ra	29	35	$2.7 \cdot 10^{-3}$	0.014
^{227}Ac	(1)[b]	(0.8)[b]	$(0.2 \cdot 10^{-6})$[c]	$(0.4 \cdot 10^{-6})$[c]
^{227}Th	(1)[b]	(0.8)[b]	$(0.2 \cdot 10^{-6})$[c]	$(0.4 \cdot 10^{-6})$[c]
^{228}Ra	(22)[d]	(22)[d]	$0.29 \cdot 10^{-3}$	$0.35 \cdot 10^{-3}$
^{228}Th	(22)[d]	(22)[d]	$0.96 \cdot 10^{-3}$	$3 \cdot 10^{-3}$
^{230}Th	19	17	$1.9 \cdot 10^{-3}$	0.012
^{231}Pa	(1)[b]	(0.8)[b]	$(0.2 \cdot 10^{-6})$[c]	$(0.4 \cdot 10^{-6})$[c]
^{231}Th	(1)[b]	(0.8)[b]	$(0.15 \cdot 10^{-3})$[b]	$(0.37 \cdot 10^{-3})$[b]
^{232}Th	22	22	$0.39 \cdot 10^{-3}$	$0.59 \cdot 10^{-3}$
^{234}Th	(23)[f]	(18)[f]	$(3.3 \cdot 10^{-3})$[f]	$(8.3 \cdot 10^{-3})$[f]
^{234}U	21 (23)[f]	25 (18)[f]	$7.3 \cdot 10^{-3}$ $(3.3 \cdot 10^{-3})$[f]	$5.1 \cdot 10^{-3}$ $(8.3 \cdot 10^{-3})$[f]
^{235}U	0.8 (1)[b]	0.5 (0.8)[b]	$0.093 \cdot 10^{-3}$ $(0.15 \cdot 10^{-3})$[b]	$0.20 \cdot 10^{-3}$ $(0.37 \cdot 10^{-3})$[b]
^{238}U	23	18	$3.3 \cdot 10^{-3}$	$8.3 \cdot 10^{-3}$

[a] Values in brackets are for ^{210}Pb, which should also apply for ^{210}Po and ^{210}Bi.

[b] Values in brackets are for ^{235}U present at 0.72% of the mass of ^{238}U, and the resulting activity concentrations should apply for ^{223}Ra (soil), ^{227}Ac (soil), ^{227}Th (soil), ^{231}Th (soil and water) and ^{231}Pa (soil).

[c] Values in brackets are 500-lower than for ^{235}U in water, as recommended by Amiro (1992, 1993). This applies for ^{223}Ra (water), ^{227}Ac (water), ^{227}Th (water) and ^{231}Pa (water).

[d] Values in brackets are for ^{232}Th (soil), which should also apply for ^{224}Ra (soil), ^{228}Th (soil) and ^{228}Ra (soil).

[e] Values in brackets are 20-fold higher than for ^{232}Th in water, as recommended by Amiro (1992, 1993). Amiro also recommended this factor for ^{228}Ra and ^{228}Th in water, but this 20-fold effect was not supported by the data found for ^{228}Ra and ^{228}Th.

[f] Values in brackets are for ^{238}U, which should also apply for ^{234}Th and ^{234}U.

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APPENDIX A: COMPARISON TO PREVIOUS ENVIRONMENTAL INCREMENTS

Amiro (1992, 1993) compiled Environmental Increment (EI) values for most of the radionuclides in this report, and the intent of his compilation was also to support assessment of nuclear waste disposal in Canada. In this Appendix we compare the present values with those of Amiro (1992, 1993), in the same order as in the main text of this document.

The soil background and EI values are presented in Table A.1, and the water values in Table A.2.

For ^{3}H, Amiro (1992, 1993) apparently based the background estimate on measurements of ^{3}H in vintage wines (already considered vintage in 1954 when the data were published), which was 3×10^{-19} atoms ^{3}H per atom ^{1}H. This is 0.036 Bq L^{-1}, which is also the EI proposed by Amiro. The background concentration listed by Amiro (1992, 1993) was 0.12 Bq L^{-1}, presumably based on the vintage wines, and because the the ^{3}H in these were isolated from natural sources for many half-lives, these data may not represent true background.

Amiro (1992, 1993) proposed two different EI values for ^{14}C, both based on specific activity. The background specific activity was 227 Bq (kg C)$^{-1}$. Using variation found in present day samples, the EI was 1 Bq (kg C)$^{-1}$. With a longer term perspective, Amiro recommended an EI of 23 Bq (kg C)$^{-1}$ to encompass variation observed for samples over the past 10^7 a.

Amiro (1992, 1993) did not specifically compute EI values for ^{137}Cs, but did compute values for ^{135}Cs and in doing this, used data for ^{137}Cs. Thus, it was possible to report ^{137}Cs values of background and EI from Amiro (1992, 1993), although they are not in the summary tables of those reports.

Table A.1: Comparison of background and EI concentrations or specific activities in soil from this report with those proposed by Amiro (1992, 1993).

Radionuclide	Background from this report, (Bq kg^{-1} unless indicated)	EI from this report, (Bq kg^{-1} unless indicated)	Background from Amiro (1992, 1993), (Bq kg^{-1} unless indicated)	EI from Amiro (1992, 1993), (Bq kg^{-1} unless indicated)
^{3}H	0.04	---	0.012	$3.6 \cdot 10^{-3}$
^{14}C[a]	239 Bq (kg C)$^{-1}$	17 Bq (kg C)$^{-1}$	227 Bq (kg C)$^{-1}$	23 Bq (kg C)$^{-1}$
^{36}Cl	1.0 Bq (kg Cl)$^{-1}$	5.6 Bq (kg Cl)$^{-1}$	not considered	not considered
^{40}K	430	210	370	0.9
^{87}Rb	25	12	55	18
^{90}Sr	2.9	7.3	7	0.5
^{129}I	$0.14 \cdot 10^{-3}$	$0.43 \cdot 10^{-3}$	$0.03 \cdot 10^{-3}$	$0.012 \cdot 10^{-3}$
^{137}Cs	6.5	20	93	66
^{210}Bi	49	110	59	71
^{210}Pb	49	110	59	71
^{210}Po	40 (49)[b]	48 (110)[b]	59	71
^{222}Rn	not relevant	not relevant	not relevant	not relevant
^{223}Ra	1	0.8	0.5	1.2
^{224}Ra	22	22	16	7
^{226}Ra	29	35	26	44
^{227}Ac	1	0.8	0.5	1.2
^{227}Th	1	0.8	0.5	1.2
^{228}Ra	22	22	16	7
^{228}Th	22	22	16	7
^{230}Th	19	17	26	44
^{231}Pa	1	0.8	0.5	1.2
^{231}Th	1	0.8	0.5	1.2
^{232}Th	22	22	16	7
^{234}Th	23	18	12	26
^{234}U	21 (23)[c]	25 (18)[c]	12	26
^{235}U	0.8 (1)[d]	0.5 (0.8)[d]	0.5	1.2
^{238}U	23	18	12	26

[a] Amiro (1992, 1993) EI based on variation over 10^{7} a

[b] Values in brackets are for ^{210}Pb, which should be numerically the same as for ^{210}Po and ^{210}Bi.

[c] Values in brackets are for ^{238}U, which should be numerically the same as for ^{234}Th and ^{234}U

[d] Values in brackets are for 0.72% of the mass of ^{238}U, and the resulting activity concentrations are the same as for ^{223}Ra as well as ^{235}U, ^{231}Pa (soil), ^{227}Ac (soil), ^{227}Th (soil) and ^{223}Ra (soil).

Table A.2: Comparison of background and EI concentrations or specific activities in water from this report with those proposed by Amiro (1992, 1993).

Radionuclide	Background from this report, (Bq L^{-1} unless indicated)	EI from this report, (Bq L^{-1} unless indicated)	Background from Amiro (1992, 1993), (Bq L^{-1} unless indicated)	EI from Amiro (1992, 1993), (Bq L^{-1} unless indicated)
^{3}H	3.2	4.2	0.12	0.036
^{14}C[a]	239 Bq (kg C)$^{-1}$	17 Bq (kg C)$^{-1}$	227 Bq (kg C)$^{-1}$	23 Bq (kg C)$^{-1}$
^{36}Cl	0.96 Bq (kg Cl)$^{-1}$	5.0 Bq (kg Cl)$^{-1}$	not considered	not considered
^{40}K	0.033	0.030	0.050	0.050
^{87}Rb	$0.26 \cdot 10^{-3}$	$0.62 \cdot 10^{-3}$	$0.9 \cdot 10^{-3}$	$0.45 \cdot 10^{-3}$
^{90}Sr	0.015	0.012	0.025	$3 \cdot 10^{-3}$
^{129}I	$0.10 \cdot 10^{-6}$	$0.07 \cdot 10^{-6}$	$0.03 \cdot 10^{-6}$	$0.043 \cdot 10^{-6}$
^{137}Cs	$1.5 \cdot 10^{-3}$	$2.0 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$	$0.2 \cdot 10^{-3}$
^{210}Bi	$6.4 \cdot 10^{-3}$	0.020	$3 \cdot 10^{-3}$	$3 \cdot 10^{-3}$
^{210}Pb	$6.4 \cdot 10^{-3}$	0.020	$3 \cdot 10^{-3}$	$3 \cdot 10^{-3}$
^{210}Po	$7.1 \cdot 10^{-3}$ $(6.4 \cdot 10^{-3})$[b]	$9.2 \cdot 10^{-3}$ (0.020)[b]	$3 \cdot 10^{-3}$	$3 \cdot 10^{-3}$
^{222}Rn	not relevant	not relevant	not relevant	not relevant
^{223}Ra	$0.2 \cdot 10^{-6}$	$0.4 \cdot 10^{-6}$	$0.1 \cdot 10^{-6}$	$0.2 \cdot 10^{-6}$
^{224}Ra	$7.8 \cdot 10^{-3}$	0.012	$4 \cdot 10^{-3}$	$10 \cdot 10^{-3}$
^{226}Ra	$2.7 \cdot 10^{-3}$	0.014	$5 \cdot 10^{-3}$	$1 \cdot 10^{-3}$
^{227}Ac	$0.2 \cdot 10^{-6}$	$0.4 \cdot 10^{-6}$	$0.1 \cdot 10^{-6}$	$0.2 \cdot 10^{-6}$
^{227}Th	$0.2 \cdot 10^{-6}$	$0.4 \cdot 10^{-6}$	$0.1 \cdot 10^{-6}$	$0.2 \cdot 10^{-6}$
^{228}Ra	$0.29 \cdot 10^{-3}$ $(0.015)^{c}$	$0.35 \cdot 10^{-3}$ $(0.036)^{c}$	$4 \cdot 10^{-3}$	$10 \cdot 10^{-3}$
^{228}Th	$0.96 \cdot 10^{-3}$ $(0.015)^{c}$	$3 \cdot 10^{-3}$ $(0.036)^{c}$	$4 \cdot 10^{-3}$	$10 \cdot 10^{-3}$
^{230}Th	$1.9 \cdot 10^{-3}$	0.012	$0.27 \cdot 10^{-3}$	$0.25 \cdot 10^{-3}$
^{231}Pa	$0.2 \cdot 10^{-6}$	$0.4 \cdot 10^{-6}$	$0.1 \cdot 10^{-6}$	$0.2 \cdot 10^{-6}$
^{231}Th	$0.15 \cdot 10^{-3}$	$0.37 \cdot 10^{-3}$	$0.06 \cdot 10^{-3}$	$0.09 \cdot 10^{-3}$
^{232}Th	$0.39 \cdot 10^{-3}$	$0.59 \cdot 10^{-3}$	$0.2 \cdot 10^{-3}$	$0.5 \cdot 10^{-3}$
^{234}Th	$3.3 \cdot 10^{-3}$	$8.3 \cdot 10^{-3}$	$1.3 \cdot 10^{-3}$	$2 \cdot 10^{-3}$
^{234}U	$7.3 \cdot 10^{-3}$ $(3.3 \cdot 10^{-3})^{d}$	$5.1 \cdot 10^{-3}$ $(8.3 \cdot 10^{-3})^{d}$	$1.3 \cdot 10^{-3}$	$2 \cdot 10^{-3}$
^{235}U	$0.093 \cdot 10^{-3}$ $(0.15 \cdot 10^{-3})^{e}$	$0.20 \cdot 10^{-3}$ $(0.37 \cdot 10^{-3})^{e}$	$0.06 \cdot 10^{-3}$	$0.09 \cdot 10^{-3}$
^{238}U	$3.3 \cdot 10^{-3}$	$8.3 \cdot 10^{-3}$	$1.3 \cdot 10^{-3}$	$2 \cdot 10^{-3}$

[a] Amiro (1992, 1993) EI based on variation over 10^{7} a
[b] Values in brackets are for ^{210}Pb, which should be numerically the same as for ^{210}Po and ^{210}Bi.
[c] Values in brackets are 20-fold higher than for ^{232}Th in water, as recommended by Amiro (1992, 1993).
[d] Values in brackets are for ^{238}U, which should be numerically the same as for ^{234}Th and ^{234}U
[e] Values in brackets are for 0.72% of ^{238}U, which should be numerically the same as for ^{223}Ra as well as ^{235}U, ^{231}Pa (soil), ^{227}Ac (soil), ^{227}Th (soil) and ^{223}Ra (soil).

APPENDIX B: MAPS OF RADIONUCLIDE CONCENTRATIONS

The first is the gamma survey coverage map, showing the regions surveyed by air and the survey (flight line) intensity. The next maps are for ^{40}K, ^{232}Th and ^{238}U, separated here into west and east. The maps for ^{232}Th and ^{238}U are labelled 'equivalent thorium' and 'equivalent uranium' because the gamma energies used for detection are emissions from short-lived radionuclide progeny rather than direct emissions from ^{232}Th and ^{238}U. The assumption of isotopic equilibrium is justified, but for semantic exactness the term 'equivalent' is used. All units are listed as ppm, equivalent to mg kg^{-1} dry weight basis.

The gamma emissions depicted on these maps represent the surface materials, and so are somewhat dependent on the amount of overburden in the region. Granite outcrops will often show relatively high gamma signatures. Unconsolidated overburden (soil), and especially peat deposits, will have lower gamma signatures because of attenuation by water, organic matter and clay minerals. In terms of biological accessibility and availability of the ^{40}K, ^{232}Th and ^{238}U, the granite outcrops may often be less important than the soils and peats even though the gamma signature of the granite outcrops is higher. To illustrate with a large landform, the Hudson's Bay Lowlands approaching Churchill Manitoba are shown in the maps to have relatively low ^{40}K, ^{232}Th and ^{238}U concentrations, and these are largely peat lands.
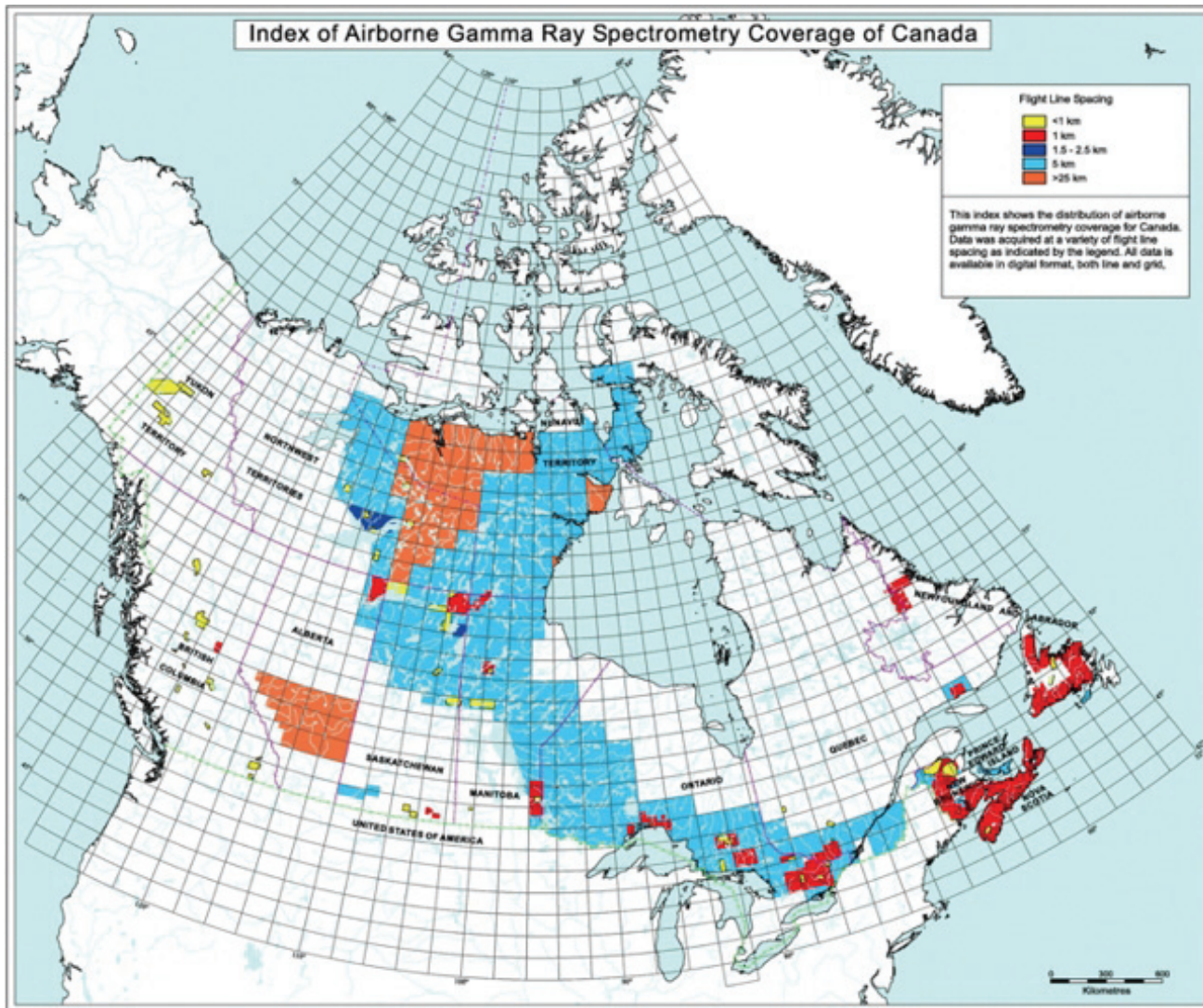
Figure B-1: Index of Airborne Gamma Ray Spectrometry Coverage of Canada.
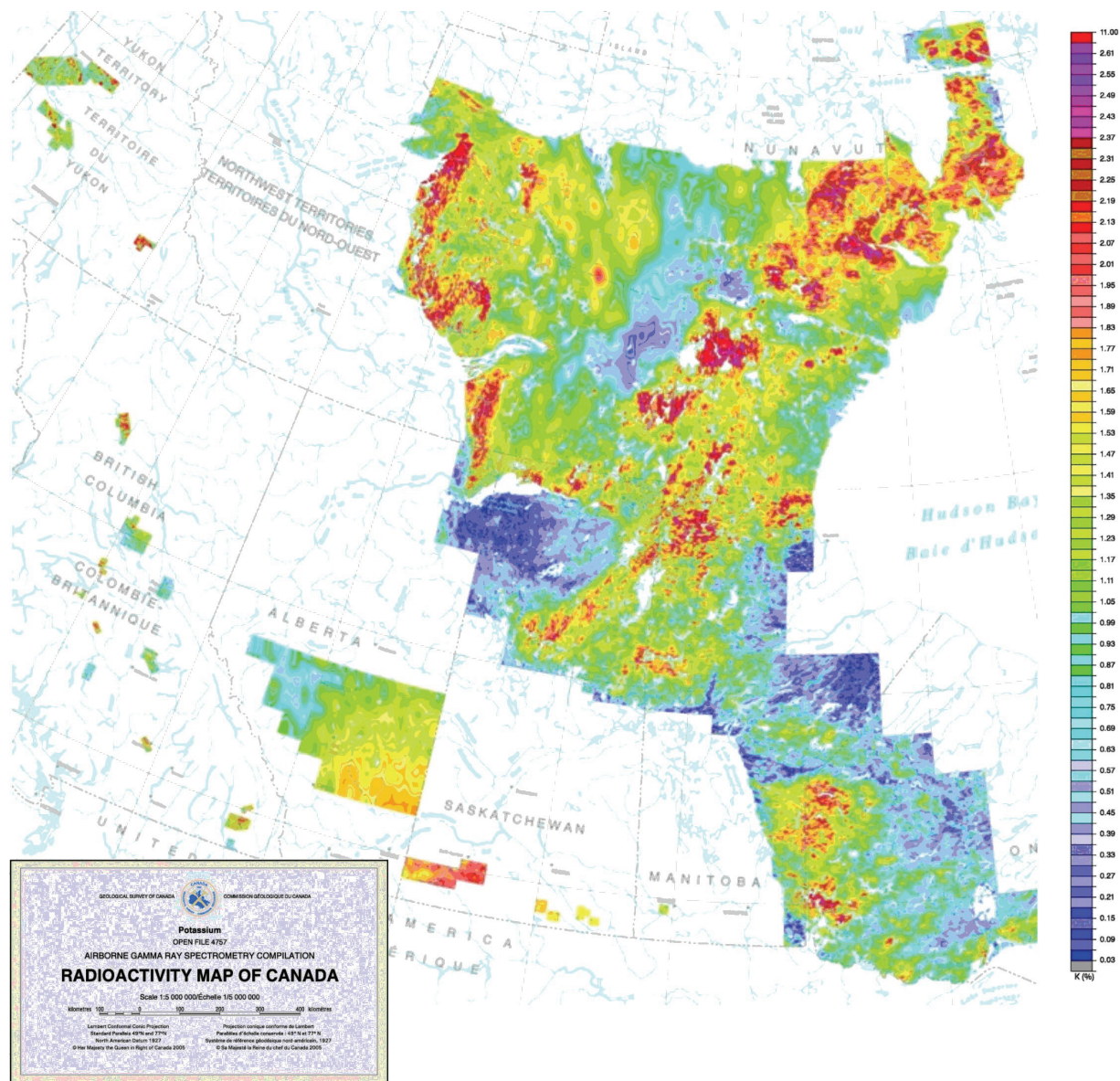
Figure B-2: Radioactivity map of Canada (West): Potassium. Scale is from 0.03 to 2.6 %K (9 to 800 Bq kg^{-1} ^{40}K) in increments of 0.06% K (19 Bq kg^{-1} ^{40}K).
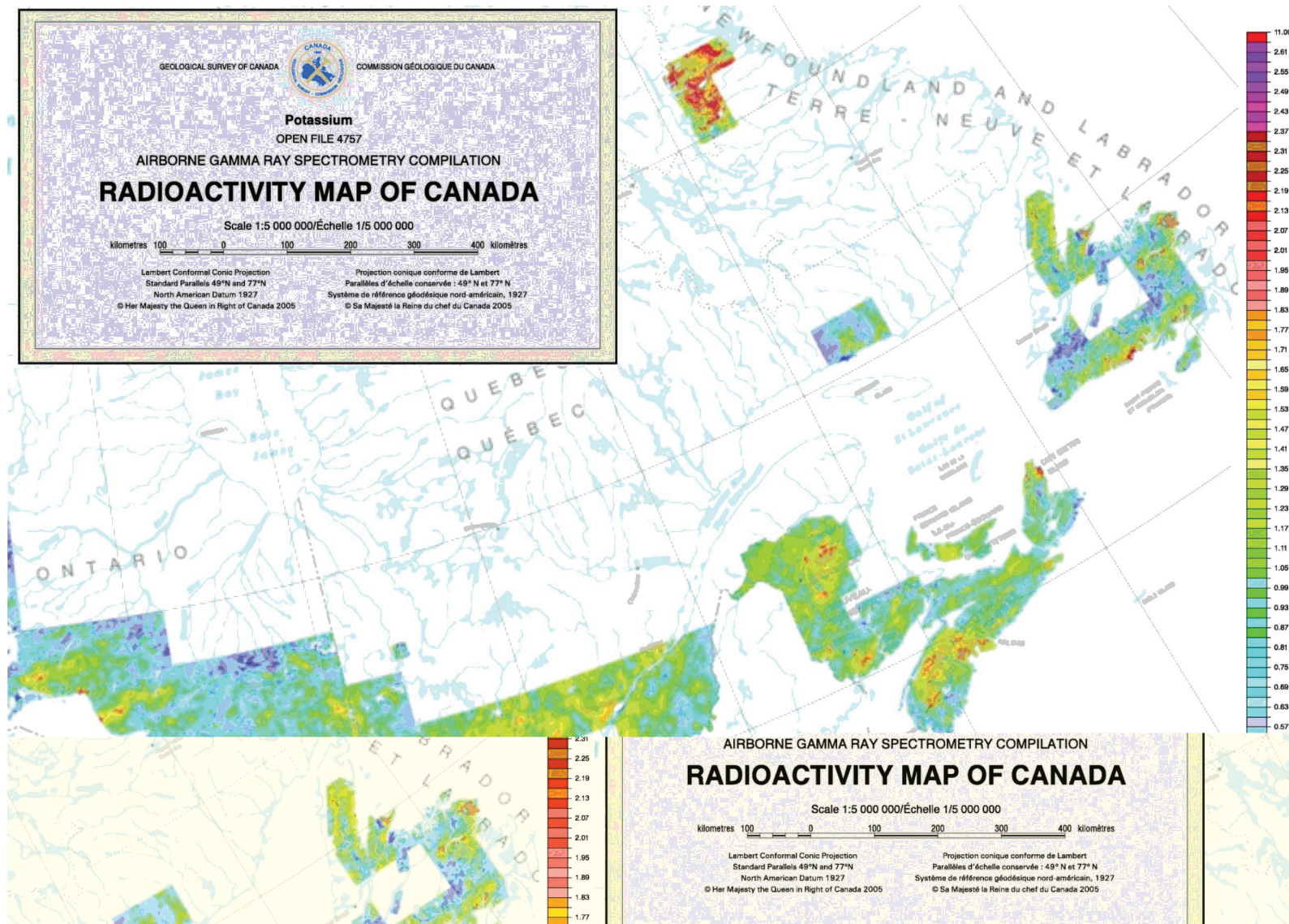
Figure B-3: Radioactivity map of Canada (East): Potassium. Scale is from 0.03 to 2.6 %K (9 to 800 Bq kg^{-1} ^{40}K) in increments of 0.06% K (19 Bq kg^{-1} ^{40}K).
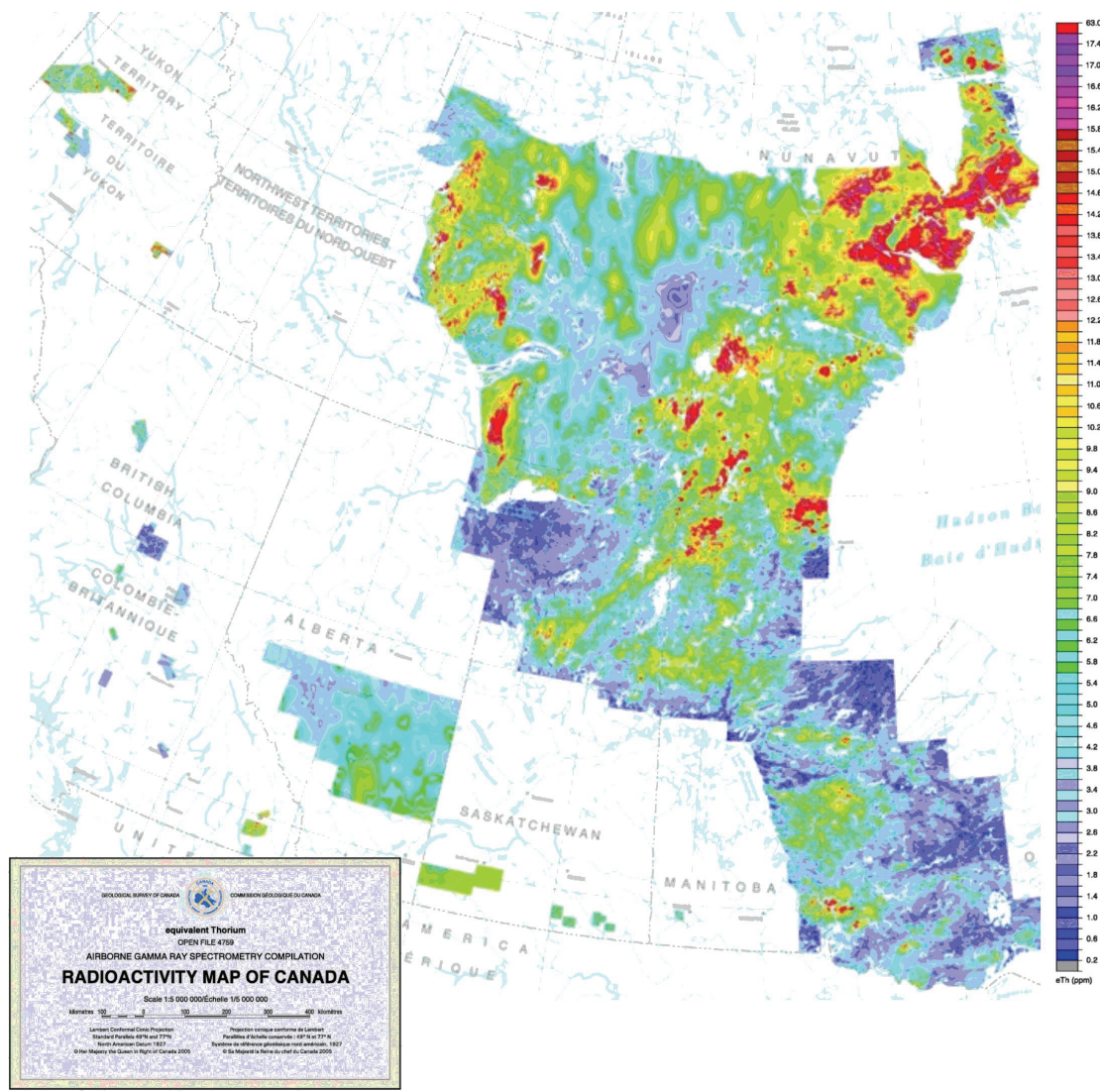
Figure B-4: Radioactivity map of Canada (West): equivalent Thorium. Scale is from 0.2 to 17 mg kg^{-1} Th (0.8 to 71 Bq ^{232}Th kg^{-1}) in increments of 0.6 mg kg^{-1} Th (2.4 Bq ^{232}Th kg^{-1}).
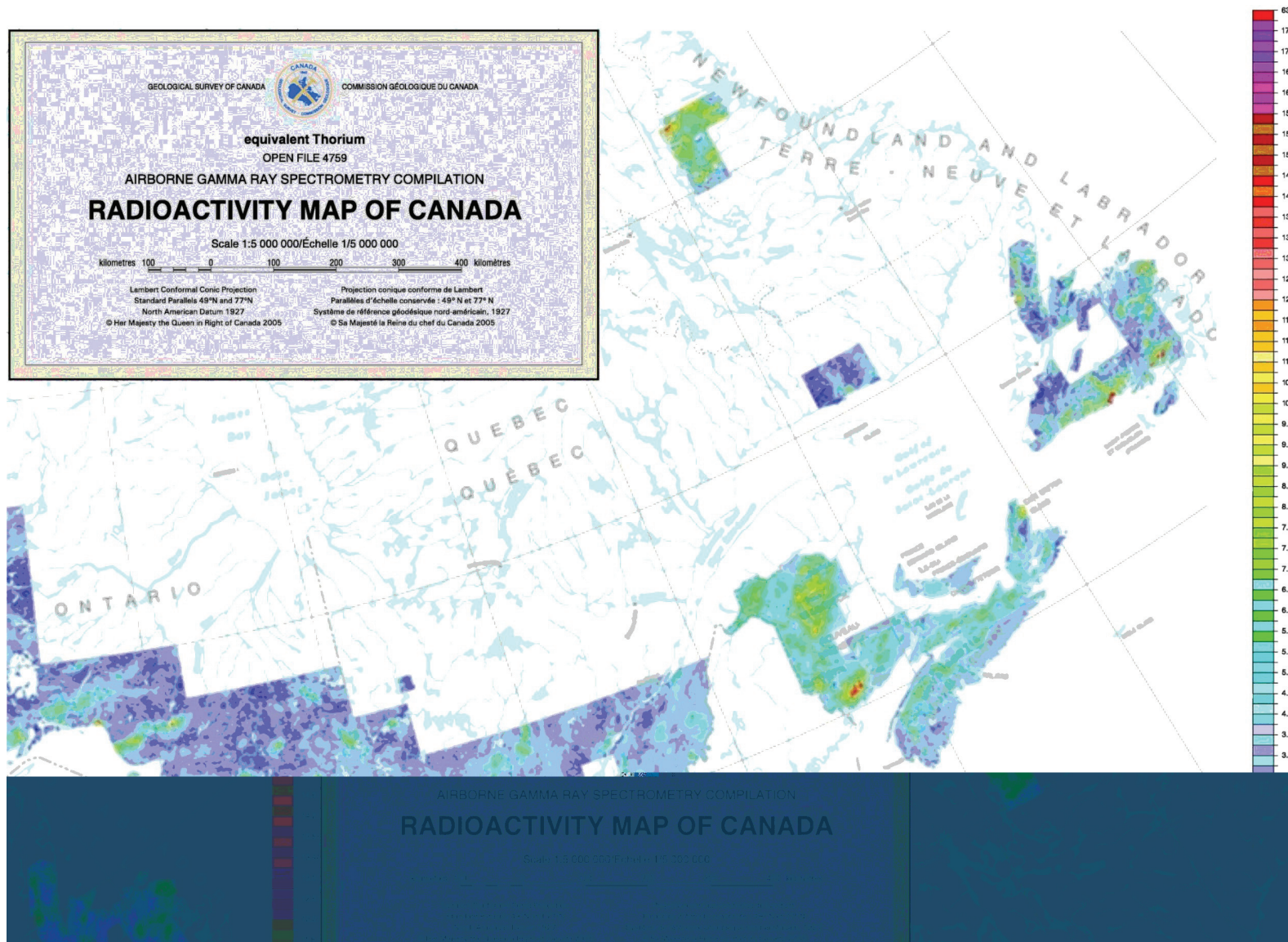
Figure B-5: Radioactivity map of Canada (East): equivalent Thorium. Scale is from 0.2 to 17 mg kg^{-1} Th (0.8 to 71 Bq ^{232}Th kg^{-1}) in increments of 0.6 mg kg^{-1} Th (2.4 Bq ^{232}Th kg^{-1}).
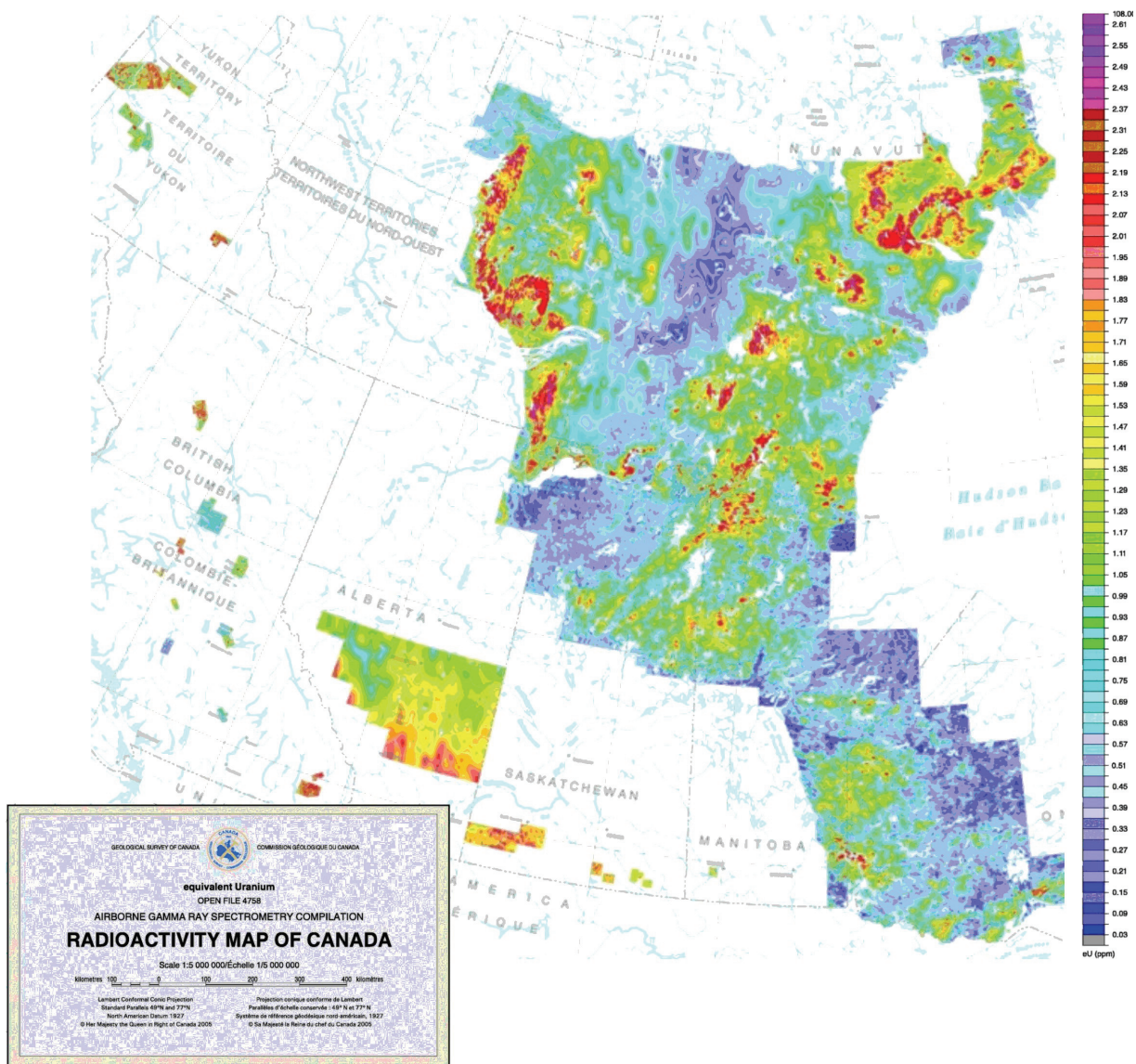
Figure B-6: Radioactivity map of Canada (West): equivalent Uranium. Scale is from 0.03 to 2.6 mg kg⁻¹ U (0.4 to 32 Bq ²³⁸U kg⁻¹) in increments of 0.06 mg kg⁻¹ U (0.7 Bq ²³⁸U kg⁻¹).
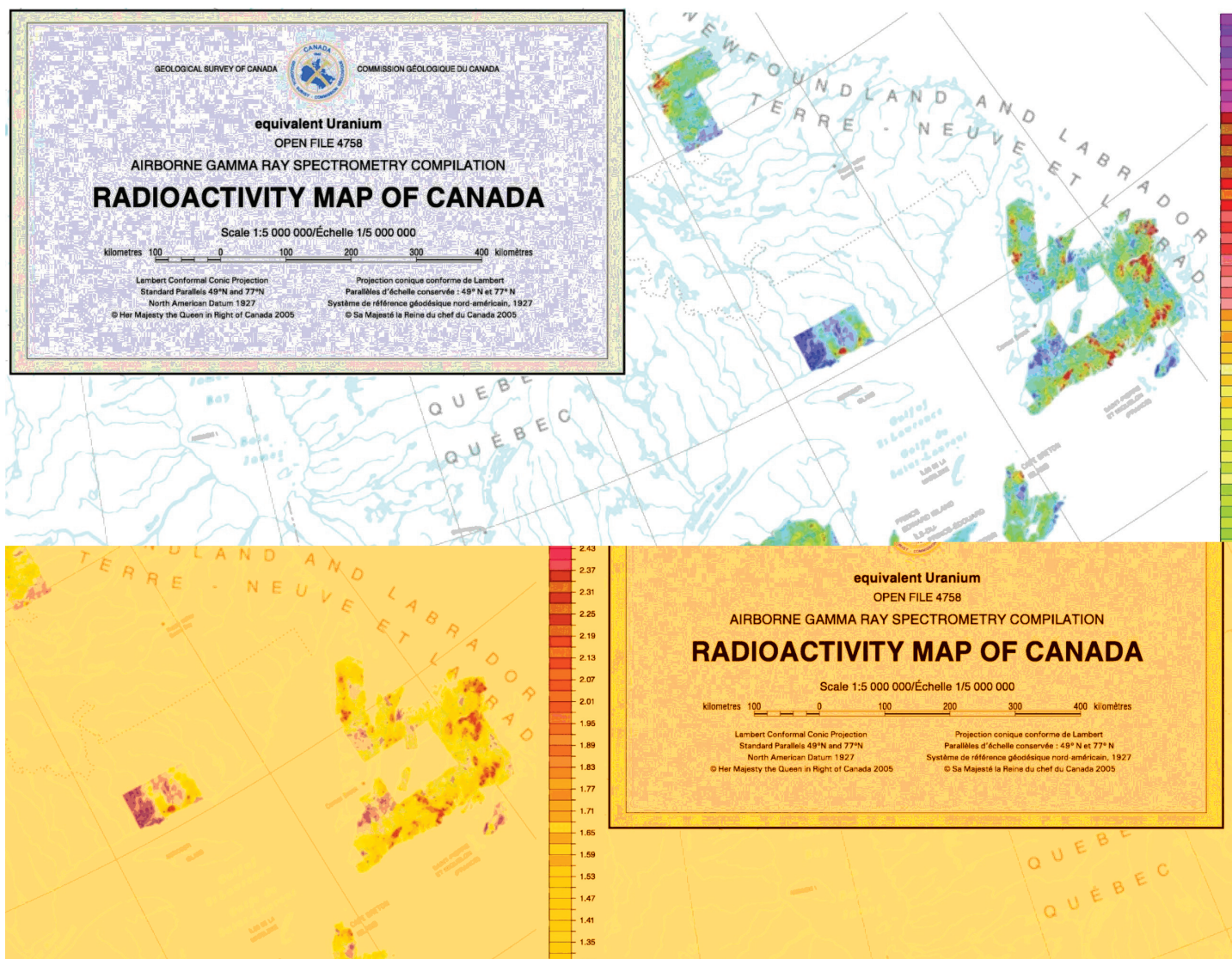
Figure B-7: Radioactivity map of Canada (East): equivalent Uranium. Scale is from 0.03 to 2.6 mg kg^{-1} U (0.4 to 32 Bq ^{238}U kg^{-1}) in increments of 0.06 mg kg^{-1} U (0.7 Bq ^{238}U kg^{-1}).

APPENDIX C: DATABASE

The following pages list the data considered, showing the fields from the database that are considered most useful. Each radionuclide is listed separately, in the same order as used in the text above.

Media	Spatial extrapolation	H-3 Activity conc. (Bq/L or Bq/kg dw)	Bibliographic source
Fish	Lake Huron	3.6	Bruce Power 2008
Fish	Lake Huron	4.2	Ontario Power Generation. 2007
Fish	Lake Ontario	5	Ontario Power Generation. 2007
Milk	S. Ontario	4.7	Bruce Power 2008
Produce	S. Ontario	3.5	Bruce Power 2008
Vegetation	S. Ontario	2.7	Ontario Power Generation. 2007
Water	Ontario Shield	<0.6	Sheppard and Sanipelli 2011
Water	Ontario Shield	<0.7	Sheppard and Sanipelli 2011
Water	Ontario Shield	<1	Sheppard and Sanipelli 2011
Water	Ontario Shield	<1.9	Ontario Power Generation. 2007
Water	Ontario Shield	<1.9	Ontario Power Generation. 2007
Water	Lake Superior	<1.9	Ontario Power Generation. 2007
Water	Ontario Shield	1.1	Sheppard and Sanipelli 2011
Water	Western Canada	1.1	Sheppard and Sanipelli 2011
Water	Eastern Canada	1.1	Sheppard and Sanipelli 2011
Water	Ontario Shield	1.3	Sheppard and Sanipelli 2011
Water	Western Canada	1.6	Sheppard and Sanipelli 2011
Water	S. Ontario	1.7	Sheppard and Sanipelli 2011
Water	Lake Ontario	1.7	Ontario Power Generation. 2007
Water	Arctic Canada	1.8	Sheppard and Sanipelli 2011
Water	Eastern Canada	1.9	Sheppard and Sanipelli 2011
Water	Lake Huron	2	Ontario Power Generation. 2007
Water	Western Canada	2	Sheppard and Sanipelli 2011
Water	Lake Erie	2.2	Sheppard and Sanipelli 2011
Water	Ontario Shield	2.4	Sheppard and Sanipelli 2011
Water	Ontario Shield	2.4	Sheppard and Sanipelli 2011
Water	Lake Huron	2.5	Ontario Power Generation. 2007
Water	Ontario Shield	2.5	Letourneau et al. 1994
Water	Lake Ontario	2.6	Ontario Power Generation. 2007
Water	Lake Erie	2.7	Ontario Power Generation. 2007
Water	Lake Huron	2.9	Ontario Power Generation. 2007
Water	Ontario Shield	2.9	Ontario Power Generation. 2007
Water	Ontario Shield	3	AECL Chalk River 2008
Water	Lake Ontario	3.3	Ontario Power Generation. 2007
Water	Lake Huron	3.5	Sheppard and Sanipelli 2011

Media	Spatial extrapolation	H-3 Activity conc. (Bq/L or Bq/kg dw)	Bibliographic source
Water	Lake Ontario	3.6	Ontario Power Generation. 2007
Water	Lake Ontario	3.9	Ontario Power Generation. 2007
Water	Lake Huron	4	Ontario Power Generation. 2007
Water	Ontario Shield	4	Sheppard and Sanipelli 2011
Water	Lake Ontario	4.2	Sheppard and Sanipelli 2011
Water	Ontario Shield	4.4	Sheppard and Sanipelli 2011
Water	Lake Huron	4.5	Ontario Power Generation. 2007
Water	Lake Huron	4.6	Ontario Power Generation. 2007
Water	Lake Ontario	4.8	Ontario Power Generation. 2007
Water	S. Ontario	4.9	Bruce Power 2008
Water	Lake Huron	5	Sheppard and Sanipelli 2011
Water	Lake Superior	5.4	Ahier and Tracy 1995
Water	S. Ontario	5.7	Ontario Power Generation. 2007
Water	S. Ontario	6.3	Ontario Power Generation. 2007
Water	S. Ontario	6.3	Sheppard and Sanipelli 2011
Water	Lake Michigan	6.6	Ahier and Tracy 1995
Water	Lake Ontario	8.7	Ahier and Tracy 1995
Water	Lake Huron	9.1	Ahier and Tracy 1995
Water	Lake Erie	12	Ahier and Tracy 1995
Water	Lake Erie	12	Bruce Power 2008
Water	Arctic Canada	12.2	Baweja et al. 1987
Water	Lake Huron	<20	Veska and Tracy 1986
Water	Arctic Canada	45	Tracy et al. 1984
Water rain	AB/SK/MB	<1.9	Ontario Power Generation. 2007
Water rain	AB/SK/MB	<1.9	Ontario Power Generation. 2007
Water rain	Eastern Canada	2	Ontario Power Generation. 2007
Water rain	Prebomb	3.3	Michel et al. 1984
Water well	S. Ontario	<1.9	Ontario Power Generation. 2007
Water well	Prebomb	0.12	Renaud et al. 2005
Water well	Ontario Shield	3.1	Renaud et al. 2005
Water well	AB/SK/MB	3.5	Nolte et al. 1991

Media	Spatial extrapolation	Mass conc. (mg/L or mg/kg dw)	C-14 Activity conc. (Bq/L or Bq/kg dw) or Specific Activity (units as indicated)	Bibliographic source
Water	Canada		218Bq/kgC	Wassenaar et al. 1991
Soil	N. Ontario		222Bq/kgC	Milton et al. 2001
Vegetation	S. Ontario		224Bq/kgC	Ontario Power Generation. 2007
Milk	S. Ontario		226Bq/kgC	Bruce Power 2008
Produce	S. Ontario		226Bq/kgC	Bruce Power 2008
Fish	S. Ontario		230Bq/kgC	Ontario Power Generation. 2007
Soil	N. Ontario		232Bq/kgC	Milton et al. 2001
Air	S. Ontario		233Bq/kgC	Bruce Power 2008
Soil	N. Ontario	5.00E+04	233Bq/kgC	Milton and Kramer 1998
Fish	S. Ontario		236Bq/kgC	Bruce Power 2008
Fish	S. Ontario		241Bq/kgC	Ontario Power Generation. 2007
Soil	N. Ontario		255Bq/kgC	Milton et al. 2001
Tissue	Global		257Bq/kgC	McNeely 1994
Milk	Global		258Bq/kgC	Milton et al. 1998
Soil	N. Ontario	4.50E+05	283Bq/kgC	Milton and Kramer 1998
Soil	N. Ontario	5.00E+04	12	Milton and Kramer 1998
Soil	N. Ontario	4.50E+05	130	Milton and Kramer 1998

Stable element data

Media	Spatial extrapolation	Mass conc.		Bibliographic source
Water	S. Ontario	2.8		Smith et al. 2004
Water	S. Ontario	8		Smith et al. 2004
Water	Global	10		Heikkinen 1994, Jonsson et al. 2007 and O'Driscoll et al. 2006
Water	Boreal	10		O'Driscoll et al. 2006
Soil	Canada	12000		Soil Landscapes of Canada 2009
Soil organic	Canada	4.00E+05		Soil Landscapes of Canada 2009

Media	Spatial extrapolation	Mass conc. (mg/L or mg/kg dw)	**Cl-36** Activity conc. (Bq/L or Bq/kg dw) or Specific Activity (units as indicated)	Bibliographic source
Exposed rock	AB/SK/MB	26 to 270	0.0004Bq/gCl	Jackson et al. 1999
Exposed rock	Eastern Canada	340	8.2E-5Bq/gCl	Osborn et al. 2007
Tissue	Prebomb	1000	0.0013Bq/gCl	Cornett et al. 1997b
Tissue	S. Ontario	na	0.002Bq/gCl	Milton et al. 2003
Tissue	Ontario Shield	1000	0.012Bq/gCl	Cornett et al. 1997b
Tissue	S. Ontario	na	0.024Bq/gCl	Milton et al. 1997a,b
Tissue	S. Ontario	na	0.04Bq/gCl	Milton et al. 2003
Water	S. Ontario	11	0.000079Bq/gCl	Sheppard and Sanipelli 2011
Water	Lake Huron	8.8	0.00034Bq/gCl	Sheppard and Sanipelli 2011
Water	Lake Ontario	1.4 to 23	0.00036Bq/gCl	Milton et al. 1994b
Water	Ontario Shield	9.9	0.00038Bq/gCl	Sheppard and Sanipelli 2011
Water	Lake Michigan	1.4 to 23	0.00047Bq/gCl	Milton et al. 1994b
Water	Lake Erie	1.4 to 23	0.00048Bq/gCl	Milton et al. 1994b
Water	Lake Ontario	17	0.00068Bq/gCl	Sheppard and Sanipelli 2011
Water	Lake Huron	1.4 to 23	0.00071Bq/gCl	Milton et al. 1994b
Water	Shield	0.45	0.00097Bq/gCl	Cornett et al. 1996
Water		na	0.0013Bq/gCl	Cornett et al. 1997b
Water	Eastern Canada	1.4 to 23	0.0016Bq/gCl	Milton et al. 1994b
Water	Eastern Canada	0.6 to 6	0.001Bq/gCl	Cornett et al. 1997a
Water	Ontario Shield	1.7	0.0045Bq/gCl	Sheppard and Sanipelli 2011
Water	Western Canada	1.2	0.0076Bq/gCl	Sheppard and Sanipelli 2011
Water rain	Eastern Canada	0.2	0.0036Bq/gCl	Cornett et al. 1997a
Water well	Prebomb	100 to 1200	0.00002Bq/gCl	Andrews and Fontes 1991
Water well	Shield	100 to 10000	0.00003Bq/gCl	Kotzer et al. 1998
Water well	Shield	17	0.00013Bq/gCl	Gascoyne et al. 1994 (also Gascoyne et al. 1992)
Water well	Shield	20	0.0003Bq/gCl	Kotzer et al. 1998
Water well	Prebomb	20	0.0006Bq/gCl	Andrews and Fontes 1991
Water well	AB/SK/MB	0.16	0.0007Bq/gCl	Fabryka-Martin 1991
Water well	AB/SK/MB	58	0.0064Bq/gCl	Nolte et al. 1990
Water	Shield	0.45	4.4E-07	Cornett et al. 1996
Water	S. Ontario	11	9.00E-07	Sheppard and Sanipelli 2011
Water	Eastern	0.6 to 6	2.E-06	Cornett et al. 1997a

Media	Spatial extrapolation	Mass conc. (mg/L or mg/kg dw)	Cl-36 Activity conc. (Bq/L or Bq/kg dw) or Specific Activity (units as indicated)	Bibliographic source
	Canada			
Water	Lake Superior	1.4 to 23	2.4E-06	Milton et al. 1994b
Water	Lake Huron	8.8	3.00E-06	Sheppard and Sanipelli 2011
Water	Ontario Shield	9.9	3.80E-06	Sheppard and Sanipelli 2011
Water	Lake Michigan	1.4 to 23	4.2E-06	Milton et al. 1994b
Water	Lake Huron	1.4 to 23	4.8E-06	Milton et al. 1994b
Water	Ontario Shield		5.3E-06	Milton et al. 1994a
Water	Lake Erie	1.4 to 23	7.4E-06	Milton et al. 1994b
Water	Ontario Shield	1.7	7.6E-06	Sheppard and Sanipelli 2011
Water	Lake Ontario	1.4 to 23	8.5E-06	Milton et al. 1994b
Water	Western Canada	1.2	8.5E-06	Sheppard and Sanipelli 2011
Water	Lake Ontario	17	1.10E-05	Sheppard and Sanipelli 2011
Water rain	S. Ontario	na	1.1E-06	Milton et al. 2003
Water rain	S. Ontario		1.2E-06	Milton et al. 1994a
Water well	Prebomb	0.60	7.E-07	Milton et al. 2003
Water well	Shield	17	2.20E-06	Gascoyne et al. 1994 (also Gascoyne et al. 1992)
Water well	Shield	20	4.E-06	Kotzer et al. 1998
Water well	Prebomb	na	6.E-06	Bentley et al. 1982
Water well	AB/SK/MB	20 to 1200	7.E-06	Andrews and Fontes 1991
Water well	AB/SK/MB	0.16	8.3E-06	Fabryka-Martin 1991
Water well	Prebomb	18	1.10E-05	Lehmann and Purtschert 1997
Water well	Prebomb	7 to 55	1.4E-05	Andrews and Fontes 1991
Water well	Prebomb	58	3.10E-05	Nolte et al. 1990
Water well	Shield	100 to 10000	0.0015	Kotzer et al. 1998

Stable element data

Media	Spatial extrapolation	Mass conc.		Bibliographic source
Soil	Canada	50		Sheppard et al. 1999, Hill 1986, Edwards et al. 1981
Soil	Shield	230		Sheppard et al. 2009a
Water rain	Global	0.25		Hayashi et al. 1998, Andrews and Fontes 1993, Cornett et al. 1997a
Water	Ontario Shield	0.42		Sheppard and Sanipelli 2011
Water	Ontario Shield	1.2		Sheppard and Sanipelli 2011
Water	West. Canada	1.2		Sheppard and Sanipelli 2011
Water	Great Lakes	1.6		Chapra et al. 2009

Media	Spatial extrapolation	Mass conc. (mg/L or mg/kg dw)	Cl-36 Activity conc. (Bq/L or Bq/kg dw) or Specific Activity (units as indicated)	Bibliographic source
Water	Ontario Shield	1.7		Sheppard and Sanipelli 2011
Water	Ontario Shield	2.1		Sheppard and Sanipelli 2011
Water	Eastern Canada	2.1		Sheppard and Sanipelli 2011
Water	S. Ontario	2.6		Cornett et al. 1996 and 1997a
Water	West. Canada	3.3		Sheppard and Sanipelli 2011
Water	Ontario Shield	3.3		Sheppard and Sanipelli 2011
Water	Ontario Shield	3.9		Sheppard and Sanipelli 2011
Water	Shield	4.6		Sheppard et al. 2009a
Water	Shield	5.3		Sheppard et al. 2009a
Water	Arctic Canada	6.1		Sheppard and Sanipelli 2011
Water	Lake Huron	7.6		Sheppard and Sanipelli 2011
Water	Lake Huron	8.8		Sheppard and Sanipelli 2011
Water	West. Canada	9.4		Sheppard and Sanipelli 2011
Water	Ontario Shield	9.9		Sheppard and Sanipelli 2011
Water	S. Ontario	11		Sheppard and Sanipelli 2011
Water	Great Lakes	12		Chapra et al. 2009
Water	N. America	13		Moran et al. 2002
Water	Lake Erie	17		Sheppard and Sanipelli 2011
Water	Lake Ontario	17		Sheppard and Sanipelli 2011
Water	Ontario Shield	18		Sheppard and Sanipelli 2011
Water	Shield	28		Sheppard et al. 2009a
Water	Ontario Shield	37		Sheppard and Sanipelli 2011
Water	Eastern Canada	42		Sheppard and Sanipelli 2011
Water	S. Ontario	61		Sheppard and Sanipelli 2011

International data

Media	Spatial extrapolation	Mass conc.	Activity conc.	Bibliographic source
Soil	Japan		0.00043Bq/gCl	Seki et al. 2007
Soil	SW_USA		0.0006Bq/gCl	Cizdziel et al. 2008
Soil	SW_USA	0.5	0.00084Bq/gCl	Phillips et al. 1988
Soil	SW_USA		0.0015Bq/gCl	Cizdziel et al. 2008
Water	SW_USA		2.6E-07	Liu et al. 1995
Water	Boreal	0.4	2.8E-06	Beasley et al. 1997
Water	Boreal	8	4.0E-06	Beasley et al. 1997
Water	SW_USA		2.0E-05	Liu et al. 1995
Water	Coastal		2.5E-5Bq/gCl	Bird et al. 1991

Media	Spatial extrapolation	Mass conc. (mg/L or mg/kg dw)	CI-36 Activity conc. (Bq/L or Bq/kg dw) or Specific Activity (units as indicated)	Bibliographic source
Water	Arid		5.4E-5Bq/gCl	Bird et al. 1991
Water	Europe	100	9.6E-5Bq/gCl	Tosaki et al. 2007
Water	NE_USA		0.00016Bq/gCl	Rao and Fehn 1997
Water	North of 60N		0.0001Bq/gCl	Green et al. 2000
Water	SW_USA		0.00044Bq/gCl	Liu et al. 1995
Water	Boreal	8	0.00048Bq/gCl	Beasley et al. 1997
Water	SW_USA		0.00048Bq/gCl	Liu et al. 1995
Water	Prebomb	0.05	0.0004Bq/gCl	Elmore et al. 1982
Water	Global		0.0006Bq/gCl	Beasley et al. 1997
Water	Asia		0.0015Bq/gCl	Green et al. 2000
Water	NW_USA		0.0047Bq/gCl	Green et al. 2000
Water	Fallout		0.029Bq/gCl	Green et al. 2000
Water well	California	8	0.00035Bq/gCl	Fehn et al. 1992
Soil	Global mid latitudes		6.90E-06	Bird et al. 1991
Soil	SW_USA	0.5	8.80E-07	Phillips et al. 1988
Water glacial	North of 60N		9.50E-08	Green et al. 2000
Water glacial	Asia		1.60E-07	Green et al. 2000
Water glacial	NW_USA		2.90E-07	Green et al. 2000
Water glacial	North of 60N	0.05	4.7E-07	Elmore et al. 1982
Water glacial	Prebomb	na	2.E-06	Andrews and Fontes 1991
Water glacial	Global		2.70E-05	Green et al. 2000
Water rain	Global	0.5	6.E-08	Andrews and Fontes 1993
Water rain	SW_USA	na	2.E-07	Bentley et al. 1982
Water rain	Coastal		2.E-06	Corcho Alvarado et al. 2005
Water well	California	8	2.90E-06	Fehn et al. 1992
Water well	Prebomb	na	4.E-06	Bentley et al. 1982
Water well	Europe	100	1.00E-05	Tosaki et al. 2007

Media	Spatial extrapolation	Mass conc. (mg/L or mg/kg dw)	K-40 Activity conc. (Bq/L or Bq/kg dw)	Bibliographic source
Soil	Canada	6.5E+03	200	Waller and Cole 1999
Soil	Canada	8.1E+03	250	Waller and Cole 1999
Soil	S. Ontario	8.4E+03	260	VandenBygaart and Protz 1995

Media	Spatial extrapolation	Mass conc. (mg/L or mg/kg dw)	K-40 Activity conc. (Bq/L or Bq/kg dw)	Bibliographic source
Soil	Eastern Canada	1.0E+04	309	Zikovsky and Blagoeva 1994b
Soil	S. Ontario	1.2E+04	373	Ontario Power Generation 2007
Soil	S. Ontario	1.2E+04	375	Ontario Power Generation 2007
Soil	S. Ontario	1.2E+04	383	Bruce Power 2008
Soil	Shield	1.3E+04	397	Zikovsky and Blagoeva 1994b
Soil	AB/SK/MB	1.3E+04	417	Kiss et al. 1988
Soil	Ontario Shield	1.4E+04	420	VandenBygaart and Protz 1999
Soil	Shield	1.4E+04	420	Zach et al. 1989
Soil	S. Ontario	1.4E+04	449	Ontario Power Generation 2007
Soil	S. Ontario	1.5E+04	460	VandenBygaart et al. 1999
Soil	AB/SK/MB	1.5E+04	470	DeJong et al. 1994
Soil	AB/SK/MB	1.5E+04	480	Kiss et al. 1988
Soil	AB/SK/MB	1.6E+04	490	Sutherland and DeJong 1990
Soil	S. Ontario	1.6E+04	491	Ontario Power Generation 2007
Soil	Canada	1.6E+04	500	Waller and Cole 1999
Soil	AB/SK/MB	1.6E+04	505	Kiss et al. 1988
Soil	AB/SK/MB	1.7E+04	519	Martz and DeJong 1990
Soil	Shield	1.7E+04	537	Zikovsky and Blagoeva 1994b
Soil	AB/SK/MB	1.8E+04	548	Kiss et al. 1988
Soil	AB/SK/MB	1.9E+04	580	Thomas 1995
Soil	S. Ontario	1.9E+04	594	Bruce Power 2008
Soil	AB/SK/MB	2.1E+04	660	DeJong et al. 1994
Soil	S. Ontario	2.4E+04	740	Tracy and Prantl 1985
Soil	S. Ontario	2.5E+04	764	Ontario Power Generation 2007
Soil	S. Ontario	2.5E+04	769	Ontario Power Generation 2007
Soil (beach)	S. Ontario	7.5E+03	232	Ontario Power Generation. 2007
Soil (beach)	S. Ontario	7.6E+03	235	Ontario Power Generation. 2007
Soil (beach)	S. Ontario	7.9E+03	246	Ontario Power Generation. 2007
Soil (beach)	S. Ontario	8.3E+03	258	Ontario Power Generation. 2007
Soil (beach)	S. Ontario	2.2E+04	679	AECL Chalk River 2008
Soil organic	Shield	3.2E+03	100	Zach et al. 1989
Water	Ontario Shield	0.3	0.009	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.4	0.011	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.4	0.012	Sheppard and Sanipelli 2011
Water	East.Canada	0.4	0.013	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.5	0.016	Sheppard and Sanipelli 2011
Water	Lake Superior	0.5	0.017	Rowan and Rasmussen 1994
Water	Great Lakes	0.6	0.019	Rowan and Rasmussen 1994
Water	Ontario Shield	0.6	0.020	Sheppard and Sanipelli 2011

Media	Spatial extrapolation	Mass conc. (mg/L or mg/kg dw)	K-40 Activity conc. (Bq/L or Bq/kg dw)	Bibliographic source
Water	Ottawa River	0.7	0.021	Rowan and Rasmussen 1994
Water	Lake Huron	0.7	0.022	Rowan and Rasmussen 1994
Water	North of 60N	0.8	0.024	Rowan and Rasmussen 1994
Water	Lake Huron	0.9	0.027	Rowan and Rasmussen 1994
Water	West. Canada	0.9	0.027	Sheppard and Sanipelli 2011
Water	East.Canada	0.9	0.027	Sheppard and Sanipelli 2011
Water	Arctic Canada	1.0	0.030	Sheppard and Sanipelli 2011
Water	Ontario Shield	1.0	0.032	Sheppard and Sanipelli 2011
Water	Lake Huron	1.1	0.034	Sheppard and Sanipelli 2011
Water	Lake Huron	1.1	0.035	Sheppard and Sanipelli 2011
Water	Lake Erie	1.2	0.039	Rowan and Rasmussen 1994
Water	Ontario Shield	1.4	0.043	Sheppard and Sanipelli 2011
Water	Lake Ontario	1.5	0.046	Sheppard and Sanipelli 2011
Water	S. Ontario	1.6	0.048	Rowan and Rasmussen 1994
Water	S. Ontario	1.6	0.049	Sheppard and Sanipelli 2011
Water	Lake Erie	1.6	0.050	Sheppard and Sanipelli 2011
Water	Lake Ontario	1.7	0.052	Rowan and Rasmussen 1994
Water	Shield	1.7	0.054	AECL Whiteshell 2008
Water	West. Canada	1.8	0.055	Sheppard and Sanipelli 2011
Water	Ontario Shield	1.9	0.059	Sheppard and Sanipelli 2011
Water	Ontario Shield	1.9	0.060	Sheppard and Sanipelli 2011
Water	AB/SK/MB	2.2	0.069	Rowan and Rasmussen 1994
Water	West. Canada	3.1	0.095	Sheppard and Sanipelli 2011
Water	S. Ontario	3.3	0.101	Sheppard and Sanipelli 2011
Water	Lake Ontario	3.5	0.11	Joshi 1984

Media	Spatial extrapolation	Mass conc. (mg/L or mg/kg dw)	Rb-87 Activity conc. (Bq/L or Bq/kg dw)	Bibliographic source
Water	Ontario Shield	0.00122	1.0E-03	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.000118	1.0E-04	Sheppard et al. 2009a
Water	Ontario Shield	0.000121	1.0E-04	Sheppard et al. 2009a
Water	West. Canada	0.00130	1.1E-03	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.00130	1.1E-03	Sheppard and Sanipelli 2011
Water	East. Canada	0.00125	1.1E-03	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.000132	1.1E-04	Sheppard et al. 2009a
Water	Ontario Shield	0.000131	1.1E-04	Sheppard et al. 2009a
Water	Ontario Shield	0.000131	1.1E-04	Sheppard et al. 2009a
Water	S. Ontario	0.00137	1.2E-03	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.000134	1.2E-04	Sheppard et al. 2009a
Water	Ontario Shield	0.000144	1.2E-04	Sheppard et al. 2009a
Water	Ontario Shield	0.000134	1.2E-04	Sheppard et al. 2009a
Water	West. Canada	0.00151	1.3E-03	Sheppard and Sanipelli 2011
Water	West. Canada	0.00149	1.3E-03	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.00151	1.3E-03	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.000148	1.3E-04	Sheppard et al. 2009a
Water	Ontario Shield	0.000146	1.3E-04	Sheppard et al. 2009a
Water	Ontario Shield	0.00157	1.4E-03	Sheppard and Sanipelli 2011
Water	Arctic Canada	0.00161	1.4E-03	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.000158	1.4E-04	Sheppard et al. 2009a
Water	Ontario Shield	0.000158	1.4E-04	Sheppard et al. 2009a
Water	Ontario Shield	0.000174	1.5E-04	Sheppard et al. 2009a
Water	West. Canada	0.000169	1.5E-04	Sheppard et al. 2009a
Water	West. Canada	0.000169	1.5E-04	Sheppard et al. 2009a
Water	West. Canada	0.000172	1.5E-04	Sheppard et al. 2009a
Water	Ontario Shield	0.000183	1.6E-04	Sheppard et al. 2009a
Water	Ontario Shield	0.000181	1.6E-04	Sheppard et al. 2009a
Water	West. Canada	0.000182	1.6E-04	Sheppard et al. 2009a
Water	West. Canada	0.000182	1.6E-04	Sheppard et al. 2009a
Water	Ontario Shield	0.000192	1.7E-04	Sheppard et al. 2009a
Water	Ontario Shield	0.000196	1.7E-04	Sheppard et al. 2009a
Water	West. Canada	0.000212	1.8E-04	Sheppard et al. 2009a
Water	Ontario Shield	0.000223	1.9E-04	Sheppard et al. 2009a
Water	Ontario Shield	0.000217	1.9E-04	Sheppard et al. 2009a
Water	Ontario Shield	0.000249	2.1E-04	Sheppard et al. 2009a
Water	Ontario Shield	0.000239	2.1E-04	Sheppard et al. 2009a
Water	Ontario Shield	0.00282	2.4E-03	Sheppard and Sanipelli 2011
Water	Lake Ontario	0.00287	2.5E-03	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.000301	2.6E-04	Sheppard et al. 2009a
Water	Ontario Shield	0.00037	3.2E-04	Sheppard et al. 2009a
Water	Ontario Shield	0.000378	3.3E-04	Sheppard et al. 2009a
Water	Ontario Shield	0.00456	3.9E-03	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.000471	4.1E-04	Sheppard et al. 2009a

Media	Spatial extrapolation	Mass conc. (mg/L or mg/kg dw)	Rb-87 Activity conc. (Bq/L or Bq/kg dw)	Bibliographic source
Water	Ontario Shield	0.00005	4.3E-05	Sheppard et al. 2009a
Water	Ontario Shield	0.00005	4.3E-05	Sheppard et al. 2009a
Water	Ontario Shield	0.000059	5.1E-05	Sheppard et al. 2009a
Water	Ontario Shield	0.000061	5.2E-05	Sheppard et al. 2009a
Water	Ontario Shield	0.000063	5.4E-05	Sheppard et al. 2009a
Water	Ontario Shield	0.00678	5.8E-03	Sheppard and Sanipelli 2011
Water	West. Canada	0.000067	5.8E-05	Sheppard et al. 2009a
Water	Ontario Shield	0.00007	6.0E-05	Sheppard et al. 2009a
Water	Ontario Shield	0.000763	6.6E-04	Sheppard et al. 2009a
Water	Ontario Shield	0.000077	6.6E-05	Sheppard et al. 2009a
Water	Ontario Shield	0.000797	6.9E-04	Sheppard et al. 2009a
Water	Ontario Shield	0.000811	7.0E-04	Sheppard et al. 2009a
Water	Ontario Shield	0.000084	7.2E-05	Sheppard et al. 2009a
Water	Ontario Shield	0.000084	7.2E-05	Sheppard et al. 2009a
Water	S. Ontario	0.00089	7.6E-04	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.000088	7.6E-05	Sheppard et al. 2009a
Water	Ontario Shield	0.000088	7.6E-05	Sheppard et al. 2009a
Water	Ontario Shield	0.00092	7.9E-04	Sheppard and Sanipelli 2011
Water	Lake Huron	0.00093	8.0E-04	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.000097	8.3E-05	Sheppard et al. 2009a
Water	Lake Erie	0.00098	8.4E-04	Sheppard and Sanipelli 2011
Water	Lake Huron	0.00098	8.4E-04	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.000101	8.7E-05	Sheppard et al. 2009a
Water	Ontario Shield	0.000101	8.7E-05	Sheppard et al. 2009a
Water	Ontario Shield	0.000104	8.9E-05	Sheppard et al. 2009a
Water	Ontario Shield	0.000103	8.9E-05	Sheppard et al. 2009a
Water	Ontario Shield	0.00111	9.5E-04	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.00011	9.5E-05	Sheppard et al. 2009a
Water	East. Canada	0.00113	9.7E-04	Sheppard and Sanipelli 2011

Media	Spatial extrapolation	Sr-90 Activity conc. (Bq/L or Bq/kg dw)	Bibliographic source
Soil	Arctic	0.55	Barrie et al. 1992
Soil	Arctic	1.8	Barrie et al. 1992
Soil	Arctic	2.9	Barrie et al. 1992
Water	Ontario Shield	0.0044	Cornett et al. 1995
Water	S. Quebec	0.0062	Roy et al. 1990
Water	North of 60N	0.015	Tracy et al. 1984
Water	North of 60N	0.015	Van Oostdam et al. 1999
Water	Ontario Shield	0.017	Joshi and McCrea 1992

Water	Ontario Shield	0.019	Roy et al. 1990
Water	Central Canada	0.021	Tracy and Prantl 1983
Water	Central Canada	0.022	Ahier and Tracy 1995
Water	Central Canada	0.024	Joshi 1984
Water	Lake Ontario	0.026	Roy et al. 1990

Media	Spatial extrapolation	Mass conc. (mg/L or mg/kg dw)	I-129 Activity conc. (Bq/L or Bq/kg dw) or Specific Activity (units as indicated)	Bibliographic source
SA rock	Ontario Shield	1.3	0.001Bq/gI	Sheppard and Sanipelli 2011
SA soil	S. Ontario	16.4	0.043Bq/gI	Sheppard and Sanipelli 2011
SA soil organic	Western Canada	11.6	0.0032Bq/gI	Sheppard and Sanipelli 2011
SA soil organic	Ontario Shield		0.0083Bq/gI	Renaud et al. 2005
SA various	S. Ontario	0.1	0.13Bq/gI	Cornett et al. 1997b
SA water	AB/SK/MB	0.16	7.2E-6Bq/gI	Fabryka-Martin 1991
SA water	Prebomb	0.0003	5.4E-5Bq/gI	Renaud et al. 2005
SA water	Shield	0.7 to 3	1E-4Bq/gI	Kotzer et al. 1998
SA water	Shield	0.001 to 0.1	2E-4Bq/gI	Kotzer et al. 1998
SA water	Ontario Shield	0.0002	0.0045Bq/gI	Renaud et al. 2005
SA water	Western Canada	0.0044	0.016Bq/gI	Sheppard and Sanipelli 2011
SA water	S. Ontario	0.0041	0.021Bq/gI	Sheppard and Sanipelli 2011
SA water	Arctic Canada	0.0015	0.023Bq/gI	Sheppard and Sanipelli 2011
SA water	Lake Ontario	0.0039	0.031Bq/gI	Sheppard and Sanipelli 2011
SA water	Eastern Canada	0.0049	0.039Bq/gI	Sheppard and Sanipelli 2011
SA water	S. Ontario	0.0024	0.044Bq/gI	Sheppard and Sanipelli 2011
SA water	Eastern Canada	0.0016	0.051Bq/gI	Sheppard and Sanipelli 2011
SA water	Ontario Shield	0.0013	0.057Bq/gI	Sheppard and Sanipelli 2011
SA water	Ontario Shield	0.0021	0.067Bq/gI	Sheppard and Sanipelli 2011
SA water	S. Ontario		0.06Bq/gI	Cornett et al. 1997b
SA water	Western Canada	0.0022	0.082Bq/gI	Sheppard and Sanipelli 2011
SA water	Lake Huron	0.0009	0.093Bq/gI	Sheppard and Sanipelli 2011
SA water	Lake Huron	0.0009	0.093Bq/gI	Sheppard and Sanipelli 2011
SA water	Ontario Shield	0.0011	0.095Bq/gI	Sheppard and Sanipelli 2011
SA water	Ontario Shield	0.0013	0.11Bq/gI	Sheppard and Sanipelli 2011
SA water	Ontario Shield	0.0007	0.11Bq/gI	Sheppard and Sanipelli 2011
SA water	Ontario Shield	0.001	0.11Bq/gI	Sheppard and Sanipelli 2011
SA water	Ontario Shield	0.001	0.11Bq/gI	Sheppard and Sanipelli 2011
SA water	Western Canada	0.0018	0.12Bq/gI	Sheppard and Sanipelli 2011
SA water	Ontario Shield	0.0009	0.14Bq/gI	Sheppard and Sanipelli 2011
SA water	Ontario Shield	0.0012	0.15Bq/gI	Sheppard and Sanipelli 2011
SA water	Lake Erie	0.0017	0.16Bq/gI	Sheppard and Sanipelli 2011
Exposed rock	Ontario Shield	1.3	4.20E-06	Sheppard and Sanipelli 2011
Exposed rock	Western Canada	<0.5	7.1E-06	Sheppard and Sanipelli 2011
Exposed	Western	<0.5	1.20E-05	Sheppard and Sanipelli 2011

Media	Spatial extrapolation	Mass conc. (mg/L or mg/kg dw)	I-129 Activity conc. (Bq/L or Bq/kg dw) or Specific Activity (units as indicated)	Bibliographic source
rock	Canada			
Soil	Ontario Shield	<0.5	5.50E-05	Sheppard and Sanipelli 2011
Soil	S. Ontario	<0.5	3.40E-04	Sheppard and Sanipelli 2011
Soil	S. Ontario	16.4	7.0E-04	Sheppard and Sanipelli 2011
Soil organic	Western Canada	11.6	2.2E-05	Sheppard and Sanipelli 2011
Soil organic	Ontario Shield		2.2E-04	Renaud et al. 2005
Water	Prebomb	0.0003	3.9E-10	Renaud et al. 2005
Water	AB/SK/MB	0.16	1.2E-09	Fabryka-Martin 1991
Water	Shield	0.001 to 0.1	2.E-09	Kotzer et al. 1998
Water	Arctic Canada	0.0015	3.4E-08	Sheppard and Sanipelli 2011
Water	North of 60N		3.5E-08	Rao and Fehn 1999
Water	North America	0.0006	4.E-08	Renaud et al. 2005
Water	North of 60N		5.90E-08	Beasley et al. 1997
Water	Western Canada	0.0044	6.9E-08	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.0013	7.4E-08	Sheppard and Sanipelli 2011
Water	Shield	0.7 to 3	8.E-08	Kotzer et al. 1998
Water	Ontario Shield	0.0007	8.0E-08	Sheppard and Sanipelli 2011
Water	Lake Huron	0.0009	8.3E-08	Sheppard and Sanipelli 2011
Water	Lake Huron	0.0009	8.3E-08	Sheppard and Sanipelli 2011
Water	Eastern Canada	0.0016	8.5E-08	Sheppard and Sanipelli 2011
Water	S. Ontario	0.0041	8.7E-08	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.0011	1.0E-07	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.001	1.1E-07	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.001	1.1E-07	Sheppard and Sanipelli 2011
Water	S. Ontario	0.0024	1.1E-07	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.0009	1.2E-07	Sheppard and Sanipelli 2011
Water	Lake Ontario	0.0039	1.2E-07	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.0002	1.2E-07	Renaud et al. 2005
Water	Ontario Shield	0.0013	1.4E-07	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.0021	1.4E-07	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.0012	1.5E-07	Sheppard and Sanipelli 2011
Water	Western Canada	0.0022	1.8E-07	Sheppard and Sanipelli 2011
Water	Eastern Canada	0.0049	1.9E-07	Sheppard and Sanipelli 2011
Water	Western Canada	0.0018	2.2E-07	Sheppard and Sanipelli 2011
Water	Lake Ontario		2.7E-07	Rao and Fehn 1997
Water	Lake Erie	0.0017	2.8E-07	Sheppard and Sanipelli 2011

Media	Spatial extrapolation	Mass conc. (mg/L or mg/kg dw)	I-129 Activity conc. (Bq/L or Bq/kg dw) or Specific Activity (units as indicated)	Bibliographic source
Stable element data				
Exposed rock	Western Canada	<0.5		Sheppard and Sanipelli 2011
Exposed rock	Western Canada	<0.5		Sheppard and Sanipelli 2011
Exposed rock	Ontario Shield	1.3		Sheppard and Sanipelli 2011
Soil	S.Ontario	<0.5		Sheppard and Sanipelli 2011
Soil	North America	0.99		Rao and Fehn 1999
Soil	Shield	2.4		Sheppard et al. 2009a
Soil	Western Canada	11.6		Sheppard and Sanipelli 2011
Soil	S.Ontario	16.4		Sheppard and Sanipelli 2011
Soil organic	Ontario Shield	<0.5		Sheppard and Sanipelli 2011
Soil organic	Shield	4		Sheppard et al. 1989
Water	North America	0.0002		Rao and Fehn 1999
Water	Ontario Shield	0.0007		Sheppard and Sanipelli 2011
Water	Ontario Shield	0.0009		Sheppard and Sanipelli 2011
Water	Lake Huron	0.0009		Sheppard and Sanipelli 2011
Water	Lake Huron	0.0009		Sheppard and Sanipelli 2011
Water	Ontario Shield	0.001		Sheppard and Sanipelli 2011
Water	Ontario Shield	0.001		Sheppard and Sanipelli 2011
Water	Ontario Shield	0.0011		Sheppard and Sanipelli 2011
Water	Shield	0.0012		Sheppard et al. 2009a
Water	Ontario Shield	0.0012		Sheppard and Sanipelli 2011
Water	Ontario Shield	0.0013		Sheppard and Sanipelli 2011
Water	Ontario Shield	0.0013		Sheppard and Sanipelli 2011
Water	Arctic Canada	0.0015		Sheppard and Sanipelli 2011
Water	Eastern Canada	0.0016		Sheppard and Sanipelli 2011
Water	Lake Erie	0.0017		Sheppard and Sanipelli 2011
Water	Western Canada	0.0018		Sheppard and Sanipelli 2011
Water	Ontario Shield	0.0021		Sheppard and Sanipelli 2011
Water	Western Canada	0.0022		Sheppard and Sanipelli 2011
Water	S. Ontario	0.0024		Sheppard and Sanipelli 2011
Water	Shield	0.0038		Sheppard et al. 2009a
Water	Lake Ontario	0.0039		Sheppard and Sanipelli 2011
Water	S. Ontario	0.0041		Sheppard and Sanipelli 2011
Water	Western Canada	0.0044		Sheppard and Sanipelli 2011
Water	Eastern	0.0049		Sheppard and Sanipelli 2011

Media	Spatial extrapolation	Mass conc. (mg/L or mg/kg dw)	I-129 Activity conc. (Bq/L or Bq/kg dw) or Specific Activity (units as indicated)	Bibliographic source
	Canada			
Water	North America	0.0093		Moran et al. 2002
Water	Shield	0.063		Sheppard et al. 2009a
Water	Shield	0.16		Sheppard et al. 1989
Water soil	North America	0.200mg/kg soil		Garrett et al. 2009

International data

Media	Spatial extrapolation	Mass conc. (mg/L or mg/kg dw)	I-129 Activity conc. (Bq/L or Bq/kg dw) or Specific Activity (units as indicated)	Bibliographic source
Sa	Prebomb		6.4E-6Bq/gI	Hou et al. 2009
SA plant	NE_USA	0.8	0.045Bq/gI	Rao et al. 2002
SA soil	Japan	35	0.0047Bq/gI	Muramatsu et al. 2008
SA soil	Japan	24	0.012Bq/gI	Muramatsu and Ohmomo 1986
SA soil	Japan	7.3	0.018Bq/gI	Matsuzaki et al. 2007
SA soil	Japan	8.9	0.018Bq/gI	Muramatsu et al. 2004
SA soil	North America	0.99	0.019Bq/gI	Rao and Fehn 1999
SA soil	Japan	15	0.026Bq/gI	Suzuki et al. 2007
SA soil	Japan	3	0.054Bq/gI	Muramatsu et al. 2008
SA soil	Russia		0.05Bq/gI	Michel et al. 2005
SA soil	Japan	26	0.086Bq/gI	Muramatsu et al. 2008
SA soil	Europe	2	0.8Bq/gI	Aumann and Gruner 1999
SA various	Prebomb	na	0.0006Bq/gI	Cornett et al. 1997b
SA water	Prebomb		9.6E-6Bq/gI	Kekli et al. 2003
SA water	North of 60N		1.9E-5Bq/gI	Kekli et al. 2003
SA water	California	0.02	6.8E-5Bq/gI	Fehn et al. 1992
SA water	North of 60N		0.00014Bq/gI	Kekli et al. 2003
SA water	Africa	0.0065	0.00042Bq/gI	Snyder and Fehn 2004
SA water	Antarct	0.00056	0.0004Bq/gI	Snyder and Fehn 2004
SA water	AustNZ	0.004	0.00096Bq/gI	Snyder and Fehn 2004
SA water	S. America	0.0014	0.0009Bq/gI	Snyder and Fehn 2004
SA water	C. America	0.0032	0.0015Bq/gI	Snyder and Fehn 2004
SA water	California	0.027	0.0017Bq/gI	Schwehr et al. 2005
SA water	Asia	0.005	0.0034Bq/gI	Snyder and Fehn 2004
SA water	North of 60N	0.0014	0.0048Bq/gI	Snyder and Fehn 2004
SA water	India	0.0009	0.0051Bq/gI	Snyder and Fehn 2004
SA water	North America	0.0093	0.0057Bq/gI	Moran et al. 2002
SA water	Prebomb		0.008Bq/gI	Oktay et al. 2000
SA water	SW_USA	0.0025	0.0096Bq/gI	Moray et al. 1999
SA water	NW_USA	0.0008	0.011Bq/gI	Snyder and Fehn 2004
SA water	Israel	0.0025	0.017Bq/gI	Snyder and Fehn 2004
SA water	SE_USA	0.005	0.019Bq/gI	Oktay et al. 2001
SA water	NE_USA	0.0009	0.055Bq/gI	Moran et al. 1999
SA water	North America	0.0002	0.064Bq/gI	Rao and Fehn 1999
SA water	Japan	0.0066	0.070Bq/gI	Muramatsu and Ohmomo 1986

Media	Spatial extrapolation	Mass conc. (mg/L or mg/kg dw)	I-129 Activity conc. (Bq/L or Bq/kg dw) or Specific Activity (units as indicated)	Bibliographic source
SA water	Europe	0.009	0.10Bq/gI	Szidat et al. 2000
SA water	Europe	0.0024	0.13Bq/gI	Snyder and Fehn 2004
SA water	Europe	0.0002	0.31Bq/gI	Moran et al. 1999
SA water	Europe	0.002	3.0Bq/gI	Szidat et al. 2000
Soil	Prebomb		4.7E-07	Szidat et al. 2000
Soil	North America	0.99	2.2E-05	Rao and Fehn 1999
Soil	Russia		6.E-05	Schmidt et al. 1998
Soil	Japan	3	6.20E-05	Muramatsu et al. 2008
Soil	Russia		1.00E-04	Michel et al. 2005
Soil	Japan	7.3	1.30E-04	Matsuzaki et al. 2007
Soil	Japan	8.9	1.40E-04	Muramatsu et al. 2004
Soil	Japan	35	0.00016	Muramatsu et al. 2008
Soil	Japan	24	1.80E-04	Muramatsu and Ohmomo 1986
Soil	Europe	2	0.002	Aumann and Gruner 1999
Soil	Scandinavia		5.50E-04	Aldahan et al. 2007a
Soil	Japan	26	0.0022	Muramatsu et al. 2008
Water	Russia		1.00E-06	Cochran et al. 2000
Water	SE_USA	0.005	1.10E-07	Oktay et al. 2001
Water	NW_USA	0.0008	1.10E-08	Snyder and Fehn 2004
Water	North of 60N		1.20E-06	Kekli et al. 2003
Water	India	0.0009	1.20E-08	Snyder and Fehn 2004
Water	S. America	0.0014	1.30E-09	Snyder and Fehn 2004
Water	North of 60N		1.70E-07	Kekli et al. 2003
Water	Asia	0.005	1.80E-08	Snyder and Fehn 2004
Water	Antarctica	0.00056	1.90E-09	Snyder and Fehn 2004
Water	Japan		2.00E-07	Aldahan et al. 2007a
Water	North of 60N		2.20E-07	Aldahan et al. 2006
Water	North of 60N		2.20E-08	Aldahan et al. 2007a
Water	ocean		2.50E-08	Oktay et al. 2001
Water	Africa	0.0065	2.80E-09	Snyder and Fehn 2004
Water	SW_USA	0.0025	2.8E-08	Moran et al. 1999
Water	Israel	0.0025	3.00E-08	Snyder and Fehn 2004
Water	Europe	0.0024	3.30E-07	Snyder and Fehn 2004
Water	Russia		3.7E-08	Beasley et al. 1997
Water	Europe	0.001	3.90E-07	Reithmeier et al. 2007
Water	California	0.027	4.70E-08	Schwehr et al. 2005
Water	Japan	0.0066	4.80E-07	Muramatsu and Ohmomo 1986
Water	NE_USA	0.0009	4.8E-08	Moran et al. 1999
Water	C. America	0.0032	5.10E-09	Snyder and Fehn 2004
Water	North of 60N		5.40E-07	Aldahan et al. 2007a
Water	AustNZ	0.004	5.70E-09	Snyder and Fehn 2004
Water	Europe	0.002	5.7E-06	Szidat et al. 2000
Water	North America	0.0093	6.0E-08	Moran et al. 2002
Water	North of 60N	0.0014	6.30E-09	Snyder and Fehn 2004

Media	Spatial extrapolation	Mass conc. (mg/L or mg/kg dw)	I-129 Activity conc. (Bq/L or Bq/kg dw) or Specific Activity (units as indicated)	Bibliographic source
Water	North of 60N		7.50E-07	Aldahan et al. 2006
Water	Scandinavia		7.70E-07	Buraglio et al. 2001
Water	Europe	0.0002	9.20E-08	Moran et al. 1999
Water	Europe	0.009	9.7E-07	Szidat et al. 2000
Water	North America	0.0002	9.7E-08	Rao and Fehn 1999
Water glacial	North of 60N		4.40E-09	Aldahan et al. 2007a
Water sea	Europe		8.00E-07	Aldahan et al. 2007a
Water sea	Europe		3.00E-06	Aldahan et al. 2007a
Water well	California	0.02	1.40E-09	Fehn et al. 1992

Media	Spatial extrapolation	Cs-137 Activity conc. (Bq/L or Bq/kg dw)	Bibliographic source
Soil	S. Ontario	0.5	Ontario Power Generation. 2007
Soil	N. Ontario	0.8	VandenBygaart and Protz 1999
Soil	North of 60N	0.83	Barrie et al. 1992
Soil	S. Ontario	0.84	Bruce Power 2008
Soil	S. Ontario	1.4	Ontario Power Generation. 2007
Soil	S. Ontario	1.5	Ontario Power Generation. 2007
Soil	North of 60N	2.7	Barrie et al. 1992
Soil	Shield	3.8	Paliouris et al. 1995
Soil	North of 60N	4.3	Barrie et al. 1992
Soil	S. Ontario	5.8	VandenBygaart and Protz 1995
Soil	AB/SK/MB	5.9	Kiss et al. 1988
Soil	S. Ontario	6	Milton et al. 2001
Soil	S. Ontario	6.3	Bruce Power 2008
Soil	S. Ontario	8	VandenBygaart et al. 1999
Soil	S. Ontario	8.5	Ontario Power Generation. 2007
Soil	S. Ontario	8.6	Ontario Power Generation. 2007
Soil	Atlantic	10	Milton et al. 2001
Soil	Shield	10	Sheppard et al. 2008
Soil	AB/SK/MB	11	Sutherland and DeJong 1990
Soil	BC	11	Waller and Cole 1999
Soil	BC	11	Waller and Cole 1999
Soil	S. Ontario	13	Milton et al. 2001
Soil	Shield	15	Sheppard et al. 2008
Soil	Shield	16	Macdonald and Laverock 1998
Soil	S. Ontario	16	Milton et al. 2001
Soil	S. Ontario	17	Milton et al. 2001
Soil	S. Ontario	17	Milton et al. 2001
Soil	AB/SK/MB	17	Thomas 1995
Soil	AB/SK/MB	18	Maule and Dudas 1989
Soil	Atlantic	20	Waller and Cole 1999
Soil	S. Ontario	25	Milton et al. 2001
Soil	Shield	30	Milton et al. 2001
Soil	Shield	30	Sheppard et al. 2008
Soil	Shield	38	Blagoeva and Zikovsky 1995
Soil	Shield	60	Zach et al. 1989
Soil	S. Ontario	<0.6	Ontario Power Generation. 2007
Soil	Canada	0.15 Chernobyl	Huda et al. 1988
Soil (beach)	S. Ontario	0.4	Ontario Power Generation. 2007
Soil (beach)	S. Ontario	0.4	Ontario Power Generation. 2007
Soil (beach)	S. Ontario	0.5	Ontario Power Generation. 2007
Soil (beach)	S. Ontario	4.5	AECL Chalk River 2008
Soil (beach)	S. Ontario	<0.4	Ontario Power Generation. 2007
Soil oganic	Shield	210	Zach et al. 1989
Soil organic	Shield	240	Paliouris et al. 1995
Soil organic	N. Ontario	290	Ali et al. 2008

Media	Spatial extrapolation	Cs-137 Activity conc. (Bq/L or Bq/kg dw)	Bibliographic source
Water	Lake Ontario	0.00012	Joshi 1987
Water	Lake Huron	0.0002	Rowan and Rasmussen 1994
Water	Lake Erie	0.00077	Rowan and Rasmussen 1994
Water	Lake Ontario	0.00083	Roy et al. 1990
Water	Ottawa River	0.001	AECL Chalk River 2008
Water	Lake Ontario	0.001	Rowan and Rasmussen 1994
Water	Great Lakes	0.0011	Ahier and Tracy 1995
Water	Great Lakes	0.0011	Joshi 1984
Water	St.Lawrence R.	0.0012	Rowan and Rasmussen 1994
Water	Shield	0.0012	Rowan and Rasmussen 1994
Water	Lake Ontario	0.0013	Durham and Joshi 1981
Water	North of 60N	0.0015	Tracy et al. 1984
Water	St.Lawrence R.	0.0017	Roy et al. 1979
Water	Lake Huron	0.0018	Durham and Joshi 1980
Water	Lake Huron	0.0022	Rowan and Rasmussen 1994
Water	Lake Superior	0.0022	Tracy and Prantl 1983
Water	North of 60N	0.0023	Rowan and Rasmussen 1994
Water	Lake Superior	0.0025	Rowan and Rasmussen 1994
Water	Ottawa River	0.0026	Joshi and McCrea 1992
Water	Lake Huron	0.003	Rowan and Rasmussen 1994
Water	Ottawa River	0.003	Roy et al. 1990
Water	Ottawa River	0.0033	Rowan and Rasmussen 1994
Water	North of 60N	0.0042	Baweja et al. 1987
Water	Shield	0.005	AECL Whiteshell 2008
Water	Ottawa River	<0.0032	Cornett et al. 1995
Water	Ottawa River	0.001	Letourneau et al. 1994
Water rain	N. Ontario	0.021	Joshi 1987

Media	Spatial extrapolation	Pb-210 Activity conc. (Bq/L or Bq/kg dw)	Bibliographic source
Soil	Ontario Shield	2.5	Cornett et al. 1984
Soil	Shield	10	Thomas 1997
Soil	Shield	<20	Sheppard et al. 2008
Soil	Shield	<20	Thomas 2000
Soil	Shield	20	Sheard 1986
Soil	Shield	24	McClean Lake Operations 2008
Soil	Shield	28	Macdonald and Laverock 1998
Soil	Shield	30	Brunskill and Wilkinson 1987
Soil	S. Ontario	30	Milton et al. 2001
Soil	S. Ontario	30	Milton et al. 2001
Soil	S. Ontario	30	Tracy and Prantl 1985
Soil	S. Ontario	50	Sheppard and Sanipelli 2011
Soil	Ontario Shield	50	Milton et al. 2001
Soil	Shield	50	Sheard et al. 1988
Soil	Canada	50	Sheppard et al. 2008
Soil	AB/SK/MB	54	Thomas 1995
Soil	Shield	60	Sheppard et al. 2008
Soil	Shield	100	Brunskill and Wilkinson 1987
Soil	BC	109	Mahon and Mathewes 1983
Soil	Shield	120	Sheard 1986
Soil	S. Ontario	140	Sheppard and Sanipelli 2011
Soil	S. Ontario	140	Tracy et al. 1983
Soil	Ontario Shield	200	Milton et al. 2001
Soil	Shield	250	Thomas 1997
Soil	Western Canada	310	Sheppard and Sanipelli 2011
Soil	Ontario Shield	800	Cornett et al. 1984
Soil organic	Shield	250	Thomas 2000
Soil organic	Shield	270	Thomas 2000
Soil organic	N. Ontario	450	Ali et al. 2008
Water	Lake Huron	<0.0002	Durham and Joshi 1980
Water	Lake Huron	0.0005	Joshi 1991
Water	N. Ontario	0.001	Clulow et al. 1998a
Water	Eastern Canada	0.002	Lupien and Grondin 1984
Water	Eastern Canada	0.0024	Lupien and Grondin 1984
Water	Shield	0.0026	Brunskill and Wilkinson 1987
Water	Eastern Canada	0.003	Lupien and Grondin 1984
Water	Ottawa River	0.0034	Joshi et al. 1991
Water	Ottawa River	0.0034	Joshi and McCrea 1992
Water	Ottawa River	0.0036	Lupien and Grondin 1984
Water	Shield	0.0045	Brunskill and Wilkinson 1985
Water	Eastern	0.005	Lupien and Grondin 1984

Media	Spatial extrapolation	Pb-210 Activity conc. (Bq/L or Bq/kg dw)	Bibliographic source
	Canada		
Water	Shield	<0.01	McClean Lake Operations 2008
Water	BC	<0.019	Mahon 1982
Water	BC	<0.019	Mahon and Mathewes 1983
Water	Shield	<0.019	Swanson 1983
Water	Shield	<0.02	Cameco 2008a
Water	AB/SK/MB	<0.02	Cameco 2007a
Water	AB/SK/MB	<0.02	Cameco 2007a
Water	North of 60N	<0.02	Veska and Eaton 1991
Water	Shield	<0.04	Waite et al. 1988
Water	N. Ontario	0.02	Clulow et al. 1998a
Water	AB/SK/MB	0.02	Key Lake Operations Report 2007
Water	Shield	0.031	Swanson 1985
Water	Shield	0.04	Kalin 1982
Water	North of 60N	0.07	Veska and Eaton 1991
Water	Shield	0.086	Hynes et al. 1987
Water rain	AB/SK/MB	0.076	Thomas 1997

Media	Spatial extrapolation	Po-210 Activity conc. (Bq/L or Bq/kg dw)	Bibliographic source
Soil	Shield	14	McClean Lake Operations 2008
Soil	Shield	20	Sheard 1986
Soil	Shield	20	Sheppard et al. 2008
Soil	Shield	30	Thomas 1997
Soil	Shield	31	Thomas 2000
Soil	Canada	38	Sheppard et al. 2008
Soil	AB/SK/MB	40	Thomas 1995
Soil	Shield	60	Sheppard et al. 2008
Soil	Shield	130	Sheard 1986
Soil	Shield	150	Thomas 1997
Soil organic	Shield	150	Thomas 2000
Soil organic	Shield	220	Thomas 2000
Soil organic	Shield	450	Ali et al. 2008
Water	Shield	0.0025	McClean Lake Operations 2008
Water	Shield	0.0041	Brunskill and Wilkinson 1987
Water	Shield	0.0045	Brunskill and Wilkinson 1985
Water	Shield	<0.005	Cameco 2008a
Water	AB/SK/MB	0.005	Cameco 2007a
Water	AB/SK/MB	0.006	Cameco 2007a
Water	BC	0.008	Mahon 1982
Water	AB/SK/MB	0.01	Cameco 2007b
Water	BC	0.012	Mahon and Mathewes 1983
Water	Shield	0.049	Hynes et al. 1987
Water rain	Shield	0.031	Thomas 1997

Media	Spatial extrapolation	Ra-226 Activity conc. (Bq/L or Bq/kg dw)	Bibliographic source
Soil	Ontario Shield	2.5	Cornett et al. 1984
Soil	Ontario Shield	9	Brunskill and Wilkinson 1987
Soil	Shield	9.7	Zikovsky and Blagoeva 1994a
Soil	Eastern Canada	14.3	Zikovsky and Blagoeva 1994a
Soil	N. Ontario	16	James F. MacLaren 1979
Soil	Shield	20	Sheppard et al. 2008
Soil	Ontario Shield	20	Sheppard and Sanipelli 2011
Soil	Shield	25	Sheppard et al. 2008
Soil	Northern Shield	26	McClean Lake Operations 2008
Soil	Shield	28	Thomas 1997
Soil	S. Ontario	30	Sheppard and Sanipelli 2011
Soil	N. SK and NWT	30	Sheard et al. 1988
Soil	Eastern Canada	30	Sheppard et al. 2008
Soil	S. Ontario	30	Tracy and Prantl 1985
Soil	Prairies	31	Martz and DeJong 1990
Soil	North of 60N	31.9	Zikovsky and Blagoeva 1994a
Soil	Prairies	32	Sutherland and DeJong 1990
Soil	Shield	35	Thomas 1997
Soil	N. Ontario	<37	Cloutier et al. 1985
Soil	Canada	37	Myrick et al. 1983
Soil	AB/SK/MB	37	Thomas 1995
Soil	Shield	37	Thomas 2000
Soil	S. Ontario	40	Sheppard and Sanipelli 2011
Soil	Shield	46	Macdonald and Laverock 1998
Soil	Shield	53	Sheard 1986
Soil	BC	77	Mahon and Mathewes 1983
Soil	S. Ontario	96	Tracy et al. 1983
Soil	Shield	170	Sheard 1986
Soil organic	Shield	38	Thomas 2000
Soil organic	Shield	40	Coker and DiLabio 1979
Soil organic	Shield	90	Thomas 2000
Soil organic	Western Canada	350	Sheppard and Sanipelli 2011
Water	Ottawa River	0.00006	Lupien and Grondin 1984
Water	Eastern Canada	0.00006	Lupien and Grondin 1984
Water	Eastern Canada	0.00015	Lupien and Grondin 1984
Water	Eastern Canada	0.00015	Lupien and Grondin 1984

Media	Spatial extrapolation	Ra-226 Activity conc. (Bq/L or Bq/kg dw)	Bibliographic source
Water	Eastern Canada	0.00025	Lupien and Grondin 1984
Water	Ontario Shield	0.00026	Brunskill and Wilkinson 1985
Water	Lake Huron	0.00037	Durham and Joshi 1980
Water	Shield	<0.005	Cameco 2008a
Water	North of 60N	<0.005	Veska and Eaton 1991
Water	BC	<0.007	Mahon and Mathewes 1983
Water	BC	<0.0007	Mahon 1982
Water	Lake Huron	0.0007	Joshi 1991
Water	Lake Ontario	0.001	Bobba and Joshi 1988, 1989
Water	Ontario Shield	0.0012	Brunskill and Wilkinson 1987
Water	Lake Ontario	0.0012	Joshi 1991
Water	Lake Ontario	0.0015	Joshi 1984
Water	North of 60N	0.00157	Baweja et al. 1987
Water	Lake Ontario	0.0018	Durham and Joshi 1981
Water	Shield	0.0028	McClean Lake Operations 2008
Water	Ontario Shield	0.0047	Pyle and Clulow 1997
Water	Ottawa River	0.0048	Joshi and McCrea 1992
Water	Ottawa River	0.0048	Joshi et al. 1991
Water	Shield	0.0049	Swanson 1983
Water	AB/SK/MB	0.005	Cameco 2007a
Water	Shield	0.0057	AECL URL 2008
Water	AB/SK/MB	0.006	Cameco 2007a
Water	Shield	0.006	Cameco 2008b
Water	Ontario Shield	0.0073	Clulow et al. 1998b
Water	AB/SK/MB	0.009	Cameco 2007b
Water	Ontario Shield	0.01	MacLaren Plansearch 1987
Water	Ontario Shield	0.012	Clulow et al. 1991
Water	Shield	0.015	Swanson 1985
Water	North of 60N	0.04	Veska and Eaton 1991
Water	Shield	0.043	Kalin 1982
Water	Shield	0.05	Hynes et al. 1987
Water	Ontario Shield	0.1	James F. MacLaren 1979
Water rain	Shield	0.0038	Thomas 1997
Water well	AB/SK/MB	0.009	Cameco 2007a
Water well	Shield	0.05	Gascoyne and Barber 1992
Water well	Shield	0.17	Gascoyne 1989

Media	Spatial extrapolation	Ra-228 Activity conc. (Bq/L or Bq/kg dw)	Bibliographic source
Soil	S. Ontario	20	Sheppard and Sanipelli 2011
Soil	S. Ontario	36	Tracy and Prantl 1985
Soil	Shield	<40	Sheppard et al. 2008
Soil	S. Ontario	40	Sheppard and Sanipelli 2011
Soil	Shield	40	Sheppard et al. 2008
Soil	Shield	40	Sheppard et al. 2008
Water	Eastern Canada	0.00008	Lupien and Grondin 1984
Water	Ottawa River	0.00018	Lupien and Grondin 1984
Water	Eastern Canada	0.00025	Lupien and Grondin 1984
Water	Eastern Canada	0.00025	Lupien and Grondin 1984
Water	CRL	0.00044	Roy et al. 1979
Water	Eastern Canada	0.00045	Lupien and Grondin 1984
Water	Lake Ontario	0.00094	Durham and Joshi 1981

Media	Spatial extrapolation	**Th-228** Activity conc. (Bq/L or Bq/kg dw)	Bibliographic source
Soil	Shield	<20	Sheppard et al. 2008
Soil	Ontario Shield	23	James F. MacLaren 1979
Soil	Ontario Shield	36	Brunskill and Wilkinson 1987
Soil	Shield	40	Sheppard et al. 2008
Soil	Shield	50	Sheppard et al. 2008
Soil organic	Western Canada	20	Sheppard and Sanipelli 2011
Water	Lake Michigan	0.000028	Joshi 1991
Water	Eastern Canada	0.0005	Lupien and Grondin 1984
Water	Eastern Canada	0.0005	Lupien and Grondin 1984
Water	Eastern Canada	0.0007	Lupien and Grondin 1984
Water	Eastern Canada	0.0007	Lupien and Grondin 1984
Water	Lake Ontario	0.001	Durham and Joshi 1981
Water	Ottawa River	0.0013	Joshi and McCrea 1992
Water	Eastern Canada	0.0014	Lupien and Grondin 1984
Water	CRL	0.0014	Roy et al. 1979
Water	Shield	0.0021	Pyle and Clulow 1997
Water	Ontario Shield	0.003	Clulow et al. 1998a
Water	Shield	<0.01	Waite et al. 1988
Water	Shield	<0.011	Swanson 1983

Media	Spatial extrapolation	**Th-230** Activity conc. (Bq/L or Bq/kg dw)	Bibliographic source
Soil	Shield	9	McClean Lake Operation 2008
Soil	Ontario Shield	11	Brunskill and Wilkinson 1987
Soil	Shield	20	Sheppard et al. 2008
Soil	Shield	30	Sheppard et al. 2008
Soil	Shield	40	Sheppard et al. 2008
Water	Ontario Shield	0.00017	Brunskill and Wilkinson 1987
Water	Ontario Shield	0.00026	Brunskill and Wilkinson 1985
Water	Ontario Shield	0.0049	Pyle and Clulow 1997
Water	Shield	<0.01	Cameco 2008a
Water	Shield	<0.011	Swanson 1983
Water	Shield	<0.036	Hynes et al. 1987
Water	Ontario Shield	0.01	Clulow et al. 1998a
Water	Shield	0.01	McClean Lake Operation 2008

Media	Spatial extrapolation	Mass conc. (mg/L or mg/kg dw)	Th-232 Activity conc. (Bq/L or Bq/kg dw)	Bibliographic source
Soil	S. Ontario	0.7	2.7	VandenBygaart and Protz 1995
Soil	S. Ontario	1.6	6.6	VandenBygaart et al. 1999
Soil	Ontario Shield	2.9	12	Sheppard and Sanipelli 2011
Soil	Shield	2.9	12	VandenBygaart and Protz 1999
Soil	AB/SK/MB	4.4	18	Kiss et al. 1988
Soil	Shield	4.9	<20	Sheppard et al. 2008
Soil	Western Canada	4.9	20	Sheppard and Sanipelli 2011
Soil	S. Ontario	5.0	20	Sheppard and Sanipelli 2011
Soil	Ontario Shield	5.4	22	Brunskill and Wilkinson 1987
Soil	AB/SK/MB	5.9	24	Kiss et al. 1988
Soil	S. Ontario	6.3	26	Sheppard and Sanipelli 2011
Soil	AB/SK/MB	6.6	27	Kiss et al. 1988
Soil	AB/SK/MB	6.6	27	Thomas 1995
Soil	AB/SK/MB	6.9	28	DeJong et al. 1994
Soil	AB/SK/MB	7.4	30	Kiss et al. 1988
Soil	AB/SK/MB	7.4	30	Sutherland and DeJong 1990
Soil	Canada	7.9	32	Myrick et al. 1983
Soil	S. Ontario	8.8	36	Tracy and Prantl 1985
Soil	Canada	9.2	37	Garrett 2009
Soil	Shield	9.8	40	Sheppard et al. 2008
Soil	AB/SK/MB	10.3	42	DeJong et al. 1994
Soil	Eastern Canada	11.0	45	Sheppard et al. 2008
Soil	Global			Reimann et al. 2007
Surface material	Shield	19	77	Soonawala, 1979
Water	Eastern Canada	2.0E-05	8.2E-05	Sheppard and Sanipelli 2011
Water	Lake Huron	2.2E-05	9.0E-05	Sheppard and Sanipelli 2011
Water	Ontario Shield	2.7E-05	1.1E-04	Sheppard and Sanipelli 2011
Water	Lake Huron	3.4E-05	1.4E-04	Sheppard and Sanipelli 2011
Water	Western Canada	3.9E-05	1.6E-04	Sheppard and Sanipelli 2011
Water	Eastern Canada	5.4E-05	2.2E-04	Sheppard and Sanipelli 2011
Water	Lake Erie	5.6E-05	2.3E-04	Sheppard and Sanipelli 2011
Water	Shield	6.1E-5	2.5E-4	Brunskill and Wilkinson 1987
Water	Shield	6.4E-5	2.6E-4	Brunskill and Wilkinson 1985
Water	Lake Ontario	6.9E-05	2.8E-04	Sheppard and Sanipelli 2011
Water	Ontario Shield	7.1E-05	2.9E-04	Sheppard and Sanipelli 2011
Water	Ontario Shield	7.4E-05	3.0E-04	Sheppard and Sanipelli 2011
Water	Ontario Shield	8.8E-05	3.6E-04	Sheppard and Sanipelli 2011
Water	Ontario Shield	1.1E-04	4.5E-04	Sheppard and Sanipelli 2011
Water	S. Ontario	1.2E-04	4.9E-04	Sheppard and Sanipelli 2011
Water	Ontario Shield	1.3E-04	5.3E-04	Sheppard and Sanipelli 2011
Water	Western Canada	1.4E-04	5.7E-04	Sheppard and Sanipelli 2011
Water	S. Ontario	1.5E-04	6.2E-04	Sheppard and Sanipelli 2011
Water	Ontario Shield	1.9E-04	7.8E-04	Sheppard and Sanipelli 2011

Media	Spatial extrapolation	Mass conc. (mg/L or mg/kg dw)	Th-232 Activity conc. (Bq/L or Bq/kg dw)	Bibliographic source
Water	Western Canada	2.1E-04	8.6E-04	Sheppard and Sanipelli 2011
Water	Ontario Shield	2.2E-04	9.0E-04	Sheppard and Sanipelli 2011
Water	Ontario Shield	2.7E-04	1.1E-03	Sheppard and Sanipelli 2011
Water	Arctic Canada	2.9E-04	1.2E-03	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.000491	0.002	Clulow et al. 1998a
Water	Ontario Shield	0.000540	0.0022	Pyle and Clulow 1997
Water	Shield		<0.011	Swanson 1983

Media	Spatial extrapolation	U-234 Activity conc. (Bq/L or Bq/kg dw) or activity ratio (units given)	Bibliographic source
Soil	Shield	21	Brunskill and Wilkinson 1987
Soil	Shield	0.92 act ratio U234/U238	CBCL 1985
Soil	Shield	1.05 act ratio U234/U238	Brunskill and Wilkinson 1987
Water	Shield	0.0036	Brunskill and Wilkinson 1987
Water	Shield	0.0076	Kronfeld et al. 2004
Water	AB/SK/MB	0.014	Ivanovich et al. 1991
Water	AB/SK/MB	1.08 act ratio U234/U238	Ivanovich et al. 1991
Water	Shield	1.15 act ratio U234/U238	Kronfeld et al. 2004
Water	Shield	1.20 act ratio U234/U238	Brunskill and Wilkinson 1987
Water well	Shield	3.0	Gascoyne 1989
Water well	Shield	2.6 act ratio U234/U238	Gascoyne 1989

Media	Spatial extrapolation	Mass conc. (mg/L or mg/kg dw)	U-235 Activity conc. (Bq/L or Bq/kg dw)	Bibliographic source
All	all		0.72% of U-nat	Amiro 1992
Soil	Ontario Shield	0.0053	0.42	Sheppard and Sanipelli 2011
Soil	BC		0.5	Waller and Cole 1999
Soil	BC		0.8	Waller and Cole 1999
Soil	S. Ontario	0.012	0.98	Sheppard and Sanipelli 2011
Soil	S. Ontario	0.014	1.1	Sheppard and Sanipelli 2011
Soil	Atlantic Canada		1.3	Waller and Cole 1999
Soil organic	Western Canada	5.8	460	Sheppard and Sanipelli 2011
Water	Eastern Canada		1.00E-05	Lupien and Grondin 1984
Water	Ontario Shield		1.70E-05	Sheppard and Sanipelli 2011
Water	Ontario Shield		2.00E-05	Sheppard and Sanipelli 2011
Water	Ontario Shield		2.30E-05	Sheppard and Sanipelli 2011
Water	Ontario Shield		2.80E-05	Sheppard and Sanipelli 2011
Water	Eastern Canada		4.00E-05	Lupien and Grondin 1984
Water	Western Canada		4.90E-05	Sheppard and Sanipelli 2011
Water	Western Canada		5.90E-05	Sheppard and Sanipelli 2011
Water	Eastern Canada		6.10E-05	Sheppard and Sanipelli 2011
Water	Ontario Shield		6.20E-05	Sheppard and Sanipelli 2011
Water	Eastern Canada		7.00E-05	Lupien and Grondin 1984
Water	Lake Ontario		7.30E-05	Sheppard and Sanipelli 2011
Water	Ontario Shield		7.40E-05	Sheppard and Sanipelli 2011
Water	Ontario Shield		7.70E-05	Sheppard and Sanipelli 2011
Water	Eastern Canada		1.00E-04	Lupien and Grondin 1984
Water	Lake Huron		1.10E-04	Sheppard and Sanipelli 2011
Water	Eastern Canada		1.20E-04	Lupien and Grondin 1984
Water	Lake Huron		1.40E-04	Sheppard and Sanipelli 2011
Water	Ontario Shield		1.50E-04	Sheppard and Sanipelli 2011
Water	Lake Erie		2.10E-04	Sheppard and Sanipelli 2011
Water	Eastern Canada		2.60E-04	Sheppard and Sanipelli 2011
Water	S. Ontario		3.70E-04	Sheppard and Sanipelli 2011
Water	S. Ontario		3.80E-04	Sheppard and Sanipelli 2011
Water	Arctic Canada		4.10E-04	Sheppard and Sanipelli 2011
Water	Western Canada		7.20E-04	Sheppard and Sanipelli 2011
Water	Ontario Shield		8.20E-04	Sheppard and Sanipelli 2011
Water	Eastern Canada		0.66% of Unat atom ratio	Lupien and Grondin 1984

Media	Spatial extrapolation	Mass conc. (mg/L or mg/kg dw)	U-238 Activity conc. (Bq/L or Bq/kg dw)	Bibliographic source
Soil	Shield	0.4	5	Sheppard et al. 2008
Soil	Shield	0.6	7.2	Thomas 1997
Soil	Shield	0.6	7	Thomas 2000
Soil	Ontario Shield	0.73	9.1	Sheppard and Sanipelli 2011
Soil	Shield	1.1	14	McClean Lake Operation 2008
Soil	N. SK and NWT	1.2	15	Sheard et al. 1988
Soil	Shield	1.4	17	Sheard 1986
Soil	Shield	1.6	20	Dunn 1981b
Soil	Ontario Shield	1.6	20	Brunskill and Wilkinson 1987
Soil	AB/SK/MB	1.6	20	Kiss et al. 1988
Soil	S. Ontario	1.7	21	Sheppard and Sanipelli 2011
Soil	S. Ontario	1.8	22	OMEE 1994
Soil	Shield	1.8	22	Sheppard et al. 2008
Soil	S. Ontario	1.9	23	Sheppard and Sanipelli 2011
Soil	AB/SK/MB	1.9	23	DeJong et al. 1994
Soil	Shield	1.9	24	Sheppard and Thibault 1984, Sheppard and Sheppard 1985
Soil	North of 60N	<2	25	DiLabio and Rencz 1980
Soil	Shield	2	25	Dunn 1981a and 1983
Soil	S. Ontario	2	25	Tracy et al. 1983
Soil	BC	2	25	Van Netten and Morley 1983, also 1982
Soil	Shield	2	25	Walker 1979
Soil	AB/SK/MB	2.05	25	Thomas 1995
Soil	AB/SK/MB	2.3	28	DeJong et al. 1994
Soil	AB/SK/MB	2.4	30	Kiss et al. 1988
Soil	Canada	2.4	30	Schumann and Gundersen 1996
Soil	North America	2.5	31	Garrett 2009
Soil	AB/SK/MB	2.5	31	Kiss et al. 1988
Soil	AB/SK/MB	2.6	32	Sutherland and DeJong 1990
Soil	Shield	2.6	32	Sheppard et al. 2008
Soil	AB/SK/MB	2.6	33	Kiss et al. 1988
Soil	Canada	2.9	36	Myrick et al. 1983
Soil	Shield	3.5	42	Thomas 1997
Soil	Shield	4.5	56	CBCL 1985
Soil	Shield	6.7	83	Sheard 1986
Soil	BC	6.96	86	Mahon and Mathewes 1983
Soil organic	Shield	1	12	Coker and DiLabio 1979
Soil organic	Shield	1.1	14	Thomas 2000
Soil organic	Shield	2.5	31	CBCL 1985
Soil organic	Shield	3.5	43	Thomas 2000
Soil organic	Shield	4.9	61	Dunn 1981a
Soil organic	Western Canada	780	9700	Sheppard and Sanipelli 2011

Media	Spatial extrapolation	Mass conc. (mg/L or mg/kg dw)	U-238 Activity conc. (Bq/L or Bq/kg dw)	Bibliographic source
Surficial material	Shield	5.9	73	Soonawala, 1979
Water	Eastern Canada	0.000012	0.00015	Lupien and Grondin 1984
Water	Ottawa River	0.00002	0.00025	Limson Zamora et al. 1998
Water	Ontario Shield	0.000031	0.00038	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.000033	0.00041	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.000040	0.00050	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.00005	0.00060	Sheppard and Sanipelli 2011
Water	Ottawa River	0.000065	0.0008	Lupien and Grondin 1984
Water	North of 60N	0.00006	0.001	Dyck and Car 1987
Water	S. Ontario	0.00007	0.001	Coker and Jonasson 1977
Water	Lake Superior	0.00008	0.001	Ahier and Tracy 1995
Water	Ontario Shield	0.00008	0.001	Cameron 1980
Water	Shield	0.0001	0.001	Cameco 2008a
Water	AB/SK/MB	0.0001	0.001	Cameco 2007a
Water	AB/SK/MB	0.0001	0.001	Cameco 2007a
Water	Shield	0.0001	0.001	Rabbit Lake Operation 2007
Water	Western Canada	0.000089	0.0011	Sheppard and Sanipelli 2011
Water	Western Canada	0.00010	0.0012	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.00010	0.0012	Sheppard and Sanipelli 2011
Water	Eastern Canada	0.00010	0.0012	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.00012	0.0015	Sheppard and Sanipelli 2011
Water	Lake Ontario	0.00012	0.0015	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.00013	0.0016	Sheppard and Sanipelli 2011
Water	North of 60N	0.00016	0.002	Baweja et al. 1987
Water	Ontario Shield	0.00017	0.002	Coker 1975
Water	Lake Huron	0.00020	0.0025	Sheppard and Sanipelli 2011
Water	Eastern Canada	0.00023	0.0028	Lupien and Grondin 1984
Water	Lake Huron	0.00023	0.0029	Sheppard and Sanipelli 2011
Water	Shield	0.00023	0.003	Pyle et al. 2001
Water	Eastern Canada	0.00024	0.003	Lupien and Grondin 1984
Water	Shield	0.00025	0.003	Thomas 1997
Water	Shield	0.00027	0.003	Kronfeld et al. 2004
Water	Ontario Shield	0.00025	0.0031	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.0003	0.0031	Brunskill and Wilkinson 1987
Water	Eastern Canada	0.00029	0.0036	Lupien and Grondin 1984
Water	Shield	0.0003	0.004	McClean Lake Operations EIS 2008
Water	Ontario Shield	0.00032	0.004	Coker and Closs 1979
Water	Lake Erie	0.00035	0.0043	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.0004	0.0045	Brunskill and Wilkinson 1985
Water	Lake Michigan	0.00038	0.005	Ahier and Tracy 1995
Water	Lake Huron	0.00039	0.005	Ahier and Tracy 1995
Water	Lake Ontario	0.00042	0.005	Ahier and Tracy 1995
Water	Eastern Canada	0.00045	0.0056	Sheppard and Sanipelli 2011

Media	Spatial extrapolation	Mass conc. (mg/L or mg/kg dw)	U-238 Activity conc. (Bq/L or Bq/kg dw)	Bibliographic source
Water	Shield	<0.0005	0.006	CBCL 1985
Water	Lake Ontario	0.0005	0.006	Joshi 1984
Water	North of 60N	0.0005	0.006	Veska and Eaton 1991
Water	Lake Eire	0.00059	0.007	Ahier and Tracy 1995
Water	North of 60N	0.0006	0.007	Veska and Eaton 1991
Water	S. Ontario	0.00063	0.0078	Sheppard and Sanipelli 2011
Water	S. Ontario	0.00065	0.0081	Sheppard and Sanipelli 2011
Water	Arctic Canada	0.00071	0.0088	Sheppard and Sanipelli 2011
Water	AB/SK/MB	0.0007	0.009	Dyck 1978
Water	Lake Ontario	0.0007	0.009	Joshi 1991
Water	Shield	0.0009	0.011	Pyle et al. 2002
Water	Ontario Shield	0.001	0.012	Clulow et al. 1998a
Water	AB/SK/MB	0.001	0.013	Ivanovich et al. 1991
Water	Western Canada	0.0013	0.016	Sheppard and Sanipelli 2011
Water	Ontario Shield	0.0014	0.017	Sheppard and Sanipelli 2011
Water	Eastern Canada	0.0014	0.017	Zikovsky 2006
Water	AB/SK/MB	0.0014	0.017	Cameco 2007b
Water	S. Ontario	0.00146	0.018	Mann and Fyfe 1985
Water	Shield	<0.0019	0.024	Hynes et al. 1987
Water	Shield	0.0022	0.027	Swanson 1985
Water	Shield	0.0032	0.040	AECL URL 2008
Water	Shield	0.0052	0.064	Swanson 1983
Water, well	AB/SK/MB	0.0001	0.001	Cameco 2007a
Water, well	Ontario Shield	0.0014	0.017	Dyck 1980
Water, well	Ontario Shield	0.0024	0.03	Wisser 2003
Water, well	Ontario Shield	0.0033	0.041	Wisser 2003
Water, well	Shield	0.0048	0.06	AECL Whiteshell 2008
Water, well	Shield	0.0065	0.081	Betcher et al. 1988
Water, well	Shield	0.092	1.14	Gascoyne 1989
Water, well	Shield	0.093	1.15	Gascoyne and Barber 1992