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PAPER

Estimation of population exposure to terrestrial gamma rays in Canada

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Abstract

Based on ground gamma ray spectrometry surveys conducted from 2007 to 2010 in populated areas across Canada (i.e. in southern Canada, excluding the northern territories), and with consideration of the exposure outdoors and indoors in various types of buildings as well as exposure to radionuclides in building materials (assuming most building materials are of local origin), the population-weighted annual effective dose from exposure to terrestrial gamma rays was estimated to be 167 $\pm$ 43 μSv. Under Canadian-specific average occupancy times, indoor exposures at home contribute 69% of the total annual effective dose, followed by 19% from indoor exposures other than at home, 6.2% from outdoor exposures and 5.8% from exposures inside vehicles. This assessment with measurements in a total of 1057 sites in populated areas across Canada is in general agreement with earlier assessments based on airborne gamma surveys mostly over unpopulated areas of Canada and truck-borne radiometric surveys along paved urban roads in four cities.

1. Introduction

Naturally occurring radionuclides of terrestrial origin (also called primordial radionuclides) are present in varying concentrations in all media in the environment. The main contribution to external exposure comes from gamma-emitting radionuclides present in trace amounts in all rocks and soils, mainly ^{40}K and the ^{238}U and ^{232}Th radioactive decay series. The activity levels are related to the types of rocks and glacial deposits from which the soils originate. There have been many surveys to determine the background levels of radionuclides in various rocks and soils, which can be related to the absorbed dose rates in air. The absorbed dose rates in air can also be measured from the gamma-emitting radionuclides in soil [1, 2].

Most gamma radiation comes from the top 20–30 cm of soil. Soil concentrations of ^{40}K and the uranium and thorium decay series vary over a factor of 20 from place-to-place in Canada [3, 4]. In Canada, direct measurements of absorbed dose rates in air have been carried out since the 1970s utilizing airborne and ground gamma ray spectrometry (AGRS, GGRS) surveys. These survey data were used to assess Canadian population exposure to terrestrial radiation [3, 4]. In 1984, the Geological Survey of Canada (GSC) published a report showing natural background radiation levels over large areas of Canada based on AGRS survey data collected in the 1970s to support geological mapping and mineral exploration in areas of high mineral potential [3]. At that time available AGRS data covered approximately 2530 000 km^2 or 28% of Canada's landmass. Most coverage was flown over unpopulated areas of Canada. Considering the exposure outdoors and indoors as well as exposure to building materials (assuming most building materials are of local origin), it was further calculated that the average Canadian population-weighted annual external dose from terrestrial radionuclides in the ground was 210 $\pm$ 130 μSv [3].

There was doubt on the reliability of the earlier AGRS surveys for estimating the external radiation dose from terrestrial radiation because most data were collected over unpopulated areas of Canada. To address this concern, in the fall of 2002, gamma ray surveys were carried out along roads in four cities in Canada (Montreal, Ottawa, Toronto and Winnipeg) by using an Exploranium GR320 gamma ray spectrometer mounted in a vehicle [4]. Approximately 600 km of roads were surveyed in each city and a total of more than 20 000 measurements were made in the four cities. It was calculated that the average population-weighted annual external dose from potassium, uranium and thorium in the ground and local building materials is 219 ± 59 μSv [4]. Even though the calculated annual external dose from these truck-borne gamma ray surveys is comparable to the value estimated from earlier AGRS surveys, there was also concern that the truck-borne gamma ray surveys along paved urban roads may not fully represent dose rates from terrestrial radionuclides in soil.

In 2007, as an important component of Health Canada's National Radon Program (NRP), Health Canada and the Geological Survey of Canada (GSC) entered into a partnership to acquire new geoscience data relevant for identifying radon prone areas in more populated regions of Canada. This included the acquisition of new AGRS survey data, *in-situ* measurements of soil gas radon (SGR) and GGRS estimates of potassium (K), equivalent uranium (eU) and equivalent thorium (eTh) concentrations in surface soils and related glacial deposits [5–7]. The term equivalent or the abbreviation 'e' is used for reporting concentrations of uranium and thorium determined by gamma ray spectrometry. These concentrations are determined indirectly from their progeny (^{214}Bi and ^{208}Tl respectively), which are assumed to be in radioactive equilibrium with their parent isotope. Potassium concentrations are measured directly from ^{40}K. All AGRS survey results (grids and line data) published for the areas reported here are available from Natural Resources Canada's Geoscience Data Repository for Geophysical and Geochemical Data at http://gdr.agg.nrcan.gc.ca/gdrdap/dap/search-eng.php. The ground surveys were carried out over 4 years from 2007 to 2010. Survey results of GGRS, SGR, and soil permeability were reported in previous publications [8–14]. Results of *in-situ* measurements of natural radioactivity in soil using GGRS are summarised here. With the data collected in populated areas across Canada, the average Canadian population-weighted annual external dose from gamma-emitting radionuclides in the ground is re-assessed.

2. Measurement activities of terrestrial gamma rays

As a contribution to the NRP the first *in-situ* survey of terrestrial radionuclides in soil was conducted in the summer of 2007 at 32 sites spaced at mean intervals of 40 km along a transect spanning southern Ontario between Ottawa and Sarnia [8]. Survey sites were located either along the outer margins of road allowances, >10 m from roads, or in farmer's fields and wooded areas where permitted by property owners. At most sites, GGRS, SGR and soil permeability measurements were conducted at five different locations at each corner and in the centre of a survey area that varied from approximately 25 m^2 to 100 m^2. At each site five, 5 min GGRS measurements were made using a fully calibrated [15, 16] Exploranium GR320 spectrometer with a single, 21 cubic inch NaI detector (www.terraplus.ca/products/radiat/g320.html). At each radon probe the spectrometer was suspended approximately 50 cm above the ground. In 2008, 2009 and 2010 most GGRS analysis were conducted using a Radiation Solutions RS-230 BGO Super-SPEC (www.radiationsolutions.ca/index.php?id-78). Each RS-230 spectrometer utilizes a single, calibrated 6.3 cubic inch BGO detector. Average potassium (K, %), equivalent uranium (eU, ppm) and equivalent thorium (eTh, ppm) concentrations were calculated for each site.

The North American Soil Geochemical Landscapes Project (NASGLP) was a tri-national initiative between Canada, the United States, and Mexico. Project protocols called for low density sampling, one sample site within each 40 km × 40 km grid square. For each 40 × 40 km cell there were multiple potential sites identified. This permitted the selection of alternate sites if, for example, the first site selected fell within a lake or was located in an otherwise inaccessible location [11]. A major addition to the Canadian project was the collection of GGRS, SGR and soil permeability data, a key element of Health Canada's NRP [12]. Instrumentation and sampling protocols used for GGRS, SGR and soil permeability have been previously reported [11, 13, 14]. All GRS measurements followed the radiometry survey guidelines outlined in the IAEA Technical Document [2]. This value-added work was undertaken at NASGLP sites at the same time as the soil sampling. The recommended NASGLP protocols [11] were suitable for most situations. However, for logistical or operational reasons, modifications were sometimes required. All field information was properly recorded on the field data sheets, including any changes to standard procedures.

In 2007, NASGLP activities were initiated in New Brunswick, Nova Scotia, and Prince Edward Island [13]. The activities continued during the 2008 and 2009 field seasons at sites along a trans-continental swath that lies roughly parallel to the Trans-Canada Highway, in parts of British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, Quebec and Newfoundland as well as additional survey sites in Nova Scotia and southern Ontario (figure 1). The 2009 field season marked the end of NASGLP activities in Canada as the result of a change in GSC priorities. Soil survey data from the NASGLP activities in 2007–2009 are available

Figure 1. Distribution of soil gas radon (SGR) and ground gamma ray spectrometry (GGRS) measurement sites sampled between 2007 and 2010. North American Soil Geochemical Landscapes Project (NASGLP) survey sites are marked in brown. Black dots represent locations of cities where urban measurements were made.

online at the GSC website [13, 14]. GGRS, SGR and soil permeability measurements were collected at 590 NASGLP sites in 10 provinces (figure 1).

In addition to the NASGLP sampling and with support from the NRP, GGRS, SGR and soil permeability measurements were conducted in a number of urban areas across Canada (figure 1). Table 1 provides a complete list of all urban centers sampled [10]. From 2007 to 2010, 467 sites were surveyed in the urban areas. For GGRS, SGR and soil permeability measurements NASGLP protocols were followed.

3. Data analysis and results of ground radiometric surveys

In the four years from 2007 to 2010, GGRS measurements were collected at 1057 sites in ten provinces across Canada. Figure 1 shows the distribution of all NASGLP and urban sample sites in Canada.

In seven provinces, major urban centers were surveyed for K, eU and eTh. In each province, field data collected in urban centers are analysed by urban center, field data collected outside of urban centers are analysed together to represent all other areas in the province. Average K (%), eU (ppm) and eTh (ppm) concentrations are shown in table 1.

For each province, population-weighted average concentrations of K (%), eU (ppm) and eTh (ppm) are calculated, as given in table 2. With a total of 1057 sites of GGRS measurements in ten provinces covering 99.67% of Canadian population, the population-weighted averages are 1.40% K, 1.47 ppm eU and 5.70 ppm eTh in Canada (note, limited data were available in the third largest province of British Columbia).

Radioelement concentrations in soil can be expressed in specific activity [18]. Results for 1057 GGRS measurements across Canada are given in table 3. Potassium dominates the activity. The total specific activities vary from 313 ± 94 Bq kg^{-1} in New Brunswick to 527 ± 99 Bq kg^{-1} in Ontario. The average, population-weighted total specific activity is 479 ± 108 Bq kg^{-1} in Canada.

4. Assessment of external exposure rate to terrestrial radiation

Theoretical γ-ray absorbed dose rates in air at 1 m above a plane and infinite homogeneous soil medium per unit radioelement concentration were determined using results of computations assuming radioactive equilibrium in the uranium and thorium decay series. For calculating average outdoor gamma ray exposure rates from concentrations of terrestrial radionuclides in soil (table 3), we use the conversion coefficients of

Table 1. Average (mean ± standard deviation) concentrations of potassium (K, %), equivalent uranium (eU, ppm) and equivalent thorium (eTh, ppm) in urban centers and North American Soil Geochemical Landscapes (NASGLP) locations outside of urban centers determined by ground gamma ray spectrometry (GGRS).

	Location	Population (2016 Census) [17]	Number of survey sites	K %	eU ppm	eTh ppm
British Columbia (BC)		4859 250	11	1.46 ± 0.40	2.02 ± 0.55	8.71 ± 2.58
Alberta (AB)	Calgary	1239 220	7	1.16 ± 0.13	1.56 ± 0.11	5.18 ± 0.76
	Edmonton	932 546	10	1.43 ± 0.08	1.79 ± 0.35	6.86 ± 0.74
	All others	2024 295	32	1.28 ± 0.22	1.68 ± 0.43	6.28 ± 1.21
Saskatchewan (SK)	Regina	215 106	20	1.38 ± 0.18	2.39 ± 0.67	7.07 ± 0.94
	Eastend	503	3	1.81 ± 0.14	2.15 ± 0.22	7.03 ± 0.21
	Eston	1061	4	1.78 ± 0.14	1.62 ± 0.24	8.71 ± 0.90
	All others	919 317	65	1.43 ± 0.32	1.56 ± 0.47	6.29 ± 1.72
Manitoba (MB)	Winnipeg	705 244	24	1.26 ± 0.18	1.34 ± 0.34	6.35 ± 0.98
	All others	608 895	21	1.26 ± 0.23	1.21 ± 0.33	5.27 ± 1.53
Ontario (ON)	Ottawa	934 243	67	1.67 ± 0.21	1.18 ± 0.27	5.67 ± 1.31
	Kingston	161 175	26	1.79 ± 0.18	1.27 ± 0.30	6.90 ± 1.26
	Toronto	2731 571	60	1.64 ± 0.14	1.50 ± 0.19	5.24 ± 1.06
	Windsor	329 144	11	1.47 ± 0.20	1.71 ± 0.27	5.46 ± 1.32
	Chatham	102 042	6	1.61 ± 0.27	1.98 ± 0.37	5.62 ± 0.98
	Sarnia	96 151	5	1.04 ± 0.21	1.27 ± 0.40	3.23 ± 0.79
	London	383 822	12	1.40 ± 0.15	1.46 ± 0.28	4.24 ± 0.87
	Woodstock	40 902	4	1.30 ± 0.05	1.55 ± 0.29	3.84 ± 0.59
	Kitchener	233 222	9	1.33 ± 0.20	1.38 ± 0.24	3.88 ± 0.82
	Guelph	12 854	4	1.27 ± 0.07	1.28 ± 0.19	4.07 ± 0.56
	All others	8850 268	143	1.54 ± 0.33	1.54 ± 0.88	5.20 ± 1.92
Quebec (QC)	Montreal	1704 694	76	1.54 ± 0.14	1.26 ± 0.19	5.41 ± 1.01
	Gatineau	276 245	38	1.80 ± 0.27	1.32 ± 0.47	5.98 ± 1.21
	All others	6245 011	39	1.19 ± 0.45	1.04 ± 0.35	4.42 ± 1.07
New Brunswick (NB)	Fredericton	101 760	20	1.29 ± 0.23	1.78 ± 0.27	7.07 ± 1.07
	All others	661 590	124	0.83 ± 0.27	0.88 ± 0.49	5.08 ± 1.37
Prince Edward Island (PEI)		146 969	9	1.27 ± 0.34	0.91 ± 0.27	4.10 ± 0.96
Nova Scotia (NS)	Halifax	403 390	61	1.23 ± 0.48	1.59 ± 0.85	4.51 ± 1.51
	All others	539 400	70	0.94 ± 0.34	1.00 ± 0.48	4.76 ± 1.48
Newfoundland and Labrador (NL)		529 426	76	1.03 ± 0.46	1.11 ± 0.42	4.55 ± 2.22

0.0417, 0.462 and 0.604 nGy h^{-1} per Bq kg^{-1} for ^{40}K, eU and eTh, respectively [19]. The summer outdoor γ-ray absorbed dose rates in air at 1 m above ground are presented in table 4.

Gamma ray dose rate varies with the moisture content of the soil. A 20% increase in soil moisture is not uncommon and will in theory decrease the gamma radiation at the soil surface by about 20%. In summer, soil has, on average, a lower soil moisture content than for the remainder of the year. Based on the analysis of over 1000 soil moisture measurements reported by the Geological Survey of Canada, the summer dose rate data (presented in table 4) must be decreased by 5% when average annual values are considered [3]

Much of Canada is snow covered for several months each year. Snow reduces the radiation exposure at the surface of the ground. The attenuation of the radiation depends not on the depth of the snow but on its water content [3]. The amount of snow on the ground varies considerably from year to year. However, it was assumed that the average snow-water equivalent on the ground during the winter months can be averaged over an entire year. As reported by Grasty *et al* [3], the data for the Great Lakes basin showed that considering the snow-water equivalent of December to April averaged over an entire year, the annual outdoor exposure rate is reduced by 20% from its measured summer value. Since most of the population of Canada resides in Quebec and Ontario, data for the Great Lakes basin is used to compute the effect of snow on the outdoor exposure rate.

Since the data presented in table 4 were gathered in the summer months, the average annual outdoor dose rate needs to be decreased by 5% for seasonal soil moisture changes, and by 20% for the attenuation effect of snow. The reduction factor for snow also applies in urban environments, because snow is cleaned

Table 2. Provincial, population-weighted averages (mean and standard deviation) for potassium (K, %), equivalent uranium (eU, ppm) and equivalent thorium (eTh, ppm) in soil determined by ground gamma ray spectrometry (GGRS).

	Population (2016 Census) [17]	Number of survey sites	K %	eU ppm	eTh ppm
British Columbia	4859 250	11	1.46 ± 0.40	2.02 ± 0.55	8.71 ± 2.58
Alberta	4196 061	49	1.28 ± 0.16	1.67 ± 0.32	6.08 ± 0.97
Saskatchewan	1135 987	92	1.42 ± 0.29	1.72 ± 0.51	6.44 ± 1.57
Manitoba	1314 139	45	1.26 ± 0.20	1.28 ± 0.34	5.85 ± 1.23
Ontario	13 875 394	347	1.56 ± 0.27	1.51 ± 0.65	5.20 ± 1.62
Quebec	8225 950	153	1.28 ± 0.38	1.09 ± 0.32	4.68 ± 1.06
New Brunswick	763 350	144	0.89 ± 0.26	1.00 ± 0.46	5.35 ± 1.33
Prince Edward Island	146 969	9	1.27 ± 0.34	0.91 ± 0.27	4.10 ± 0.96
Nova Scotia	942 790	131	1.06 ± 0.40	1.25 ± 0.64	4.65 ± 1.49
Newfoundland and Labrador	529 426	76	1.03 ± 0.46	1.11 ± 0.42	4.55 ± 2.22
Total	35 989 316	1057	1.40 ± 0.30	1.47 ± 0.50	5.70 ± 1.53

Table 3. Average, population-weighted (mean and standard deviation) specific activity levels derived from potassium (K), equivalent uranium (eU) and equivalent thorium (eTh) concentrations determined by ground gamma ray spectrometry (GGRS).

	Population (2016 Census) [17]	K Bq kg^{-1}	eU Bq kg^{-1}	eTh Bq kg^{-1}	Total Bq kg^{-1}
British Columbia	4859 250	457 ± 125	25.0 ± 6.8	35.4 ± 10.5	517 ± 142
Alberta	4196 061	400 ± 51	20.6 ± 3.9	24.7 ± 4.0	445 ± 59
Saskatchewan	1135 987	445 ± 92	21.2 ± 6.3	26.2 ± 6.4	492 ± 104
Manitoba	1314 139	394 ± 64	15.8 ± 4.1	23.8 ± 5.0	434 ± 73
Ontario	13 875 394	488 ± 84	18.6 ± 8.0	21.1 ± 6.6	527 ± 99
Quebec	8225 950	402 ± 119	13.5 ± 4.0	19.0 ± 4.3	434 ± 127
New Brunswick	763 350	279 ± 83	12.4 ± 5.7	21.7 ± 6.4	313 ± 94
Prince Edward Island	146 969	398 ± 106	11.2 ± 3.3	16.7 ± 3.9	425 ± 114
Nova Scotia	942 790	333 ± 125	15.5 ± 7.9	18.9 ± 6.1	367 ± 139
Newfoundland and Labrador	529 426	322 ± 144	13.7 ± 5.2	18.5 ± 9.0	355 ± 158
Total	35 989 316	438 ± 95	18.2 ± 6.1	23.1 ± 6.2	479 ± 108

only on paved roads (a small portion of urban areas), and in many cases simply piled up on the roadsides. Applying these correction factors, the annual outdoor γ-ray dose rates, derived from summer outdoor values, are shown in table 5.

The annual average outdoor γ-ray absorbed dose rates vary from 23 ± 7 nGy h^{-1} in New Brunswick to 39 ± 11 nGy h^{-1} in British Columbia. The population-weighted average annual outdoor γ-ray dose rate for Canada is 30.6 ± 8.0 nGy h^{-1} where potassium contributes 45%, followed by thorium 35% and uranium 20%. Since only 11 sites were surveyed in British Columbia (BC) outside most populated areas of the province, the estimated exposure rate for BC may not be representative and may likely contain significant uncertainty. If we exclude data from BC, the population-weighted average annual outdoor γ-ray dose rate for Canada will then be 29.3 ± 7.5 nGy h^{-1}, slightly lower than 30.6 ± 8.0 nGy h^{-1} given in table 5, but well within the variation range.

5. Estimate of annual population exposure to terrestrial γ-rays

For calculating average outdoor gamma ray effective dose rates from absorbed dose rates in air (table 5), we considered the age-group specific conversion coefficients for infants, children and adults [19]. As shown in table 6, the Canadian population-weighted average conversion coefficients are 0.724, 0.687 and 0.711 Sv Gy^{-1} for radioelements K, eU and eTh, respectively.

Table 4. Average (mean and standard deviation) summer outdoor γ-ray absorbed dose rates of potassium (K), equivalent uranium (eU) and equivalent thorium (eTh) in air in ten provinces of Canada.

	Population (2016 Census) [17]	K nGy h^{-1}	eU nGy h^{-1}	eTh nGy h^{-1}	Total nGy h^{-1}
British Columbia	4859 250	19.1 ± 5.2	11.5 ± 3.1	21.7 ± 6.4	52.3 ± 14.8
Alberta	4196 061	16.7 ± 2.1	9.5 ± 1.8	15.2 ± 2.4	41.4 ± 6.4
Saskatchewan	1135 987	18.6 ± 3.8	9.8 ± 2.9	16.1 ± 3.9	44.4 ± 10.6
Manitoba	1314 139	16.5 ± 2.7	7.3 ± 1.9	14.6 ± 3.1	38.3 ± 7.6
Ontario	13 875 394	20.4 ± 3.5	8.5 ± 3.7	13.0 ± 4.0	41.9 ± 11.2
Quebec	8225 950	16.8 ± 5.0	6.2 ± 1.8	11.7 ± 2.7	34.7 ± 9.4
New Brunswick	763 350	11.7 ± 3.5	5.7 ± 2.6	13.3 ± 3.3	30.7 ± 9.4
Prince Edward Island	146 969	16.6 ± 4.5	5.2 ± 1.5	10.2 ± 2.4	32.0 ± 8.4
Nova Scotia	942 790	13.9 ± 5.2	7.1 ± 3.6	11.6 ± 3.7	32.6 ± 12.6
Newfoundland and Labrador	529 426	13.5 ± 6.0	6.3 ± 2.4	11.4 ± 5.5	31.1 ± 13.9
Total	35 989 316	18.3 ± 4.0	8.4 ± 2.8	14.2 ± 3.8	40.9 ± 10.6

Table 5. Average (mean and standard deviation) annual outdoor γ-ray absorbed dose rates of potassium (K), equivalent uranium (eU) and equivalent thorium (eTh) in air in ten provinces of Canada corrected for soil moisture and snow-water equivalence.

	Population (2016 Census) [17]	K nGy h^{-1}	eU nGy h^{-1}	eTh nGy h^{-1}	Total nGy h^{-1}
British Columbia	4859 250	14.3 ± 3.9	8.6 ± 2.3	16.3 ± 4.8	39.2 ± 11.1
Alberta	4196 061	12.5 ± 1.6	7.1 ± 1.4	11.4 ± 1.8	31.0 ± 4.8
Saskatchewan	1135 987	13.9 ± 2.9	7.3 ± 2.2	12.1 ± 2.9	33.3 ± 8.0
Manitoba	1314 139	12.4 ± 2.0	5.5 ± 1.4	10.9 ± 2.3	28.8 ± 5.7
Ontario	13 875 394	15.3 ± 2.7	6.4 ± 2.8	9.7 ± 3.0	31.4 ± 8.4
Quebec	8225 950	12.6 ± 3.7	4.7 ± 1.4	8.8 ± 2.0	26.0 ± 7.1
New Brunswick	763 350	8.7 ± 2.6	4.3 ± 2.0	10.0 ± 2.5	23.0 ± 7.0
Prince Edward Island	146 969	12.5 ± 3.3	3.9 ± 1.2	7.7 ± 1.8	24.0 ± 6.3
Nova Scotia	942 790	10.4 ± 3.9	5.3 ± 2.7	8.7 ± 2.8	24.5 ± 9.4
Newfoundland and Labrador	529 426	10.1 ± 4.5	4.7 ± 1.8	8.5 ± 4.2	23.3 ± 10.5
Total	35 989 316	13.7 ± 3.0	6.3 ± 2.1	10.7 ± 2.9	30.6 ± 8.0

Table 6. Conversion coefficients from absorbed dose in air to effective dose for terrestrial gamma rays from potassium (K), equivalent uranium (eU) and equivalent thorium (eTh).

	Population (2016 Census) [17]	K (Sv/Gy)	eU (Sv/Gy)	eTH (Sv/Gy)
Infants (<1 year)	383 216	0.926	0.899	0.907
Children (1–12 years)	4716 232	0.803	0.766	0.798
Adults (>12 years)	31 010 039	0.709	0.672	0.695
Canadians	36 109 487	0.724	0.687	0.711

Using these conversion coefficients, the average annual outdoor γ-ray effective dose rates in ten provinces of Canada are calculated and shown in table 7. The population-weighted average annual outdoor γ-ray effective dose rate is 21.8 ± 5.7 nSv h^{-1} in Canada.

People are exposed to terrestrial gamma radiation everywhere (outdoors and indoors) at all times. Therefore, time-activity data are a key component for population exposure assessment. The General Social Survey—Canadians at work and home conducted by Statistics Canada [20, 21] provided updated time

Table 7. Average (mean and standard deviation) annual outdoor γ-ray effective dose rates of potassium (K), equivalent uranium (eU) and equivalent thorium (eTh) in ten provinces of Canada.

	Population (2016 Census) [17]	K nSv h^{-1}	U nSv h^{-1}	Th nSv h^{-1}	Total nSv h^{-1}
British Columbia (BC)	4859 250	10.4 ± 2.8	5.9 ± 1.6	11.6 ± 3.4	27.8 ± 7.9
Alberta (AB)	4196 061	9.1 ± 1.2	4.9 ± 0.9	8.1 ± 1.3	22.0 ± 3.4
Saskatchewan (SK)	1135 987	10.1 ± 2.1	5.0 ± 1.5	8.6 ± 2.1	23.6 ± 5.7
Manitoba (MB)	1314 139	9.0 ± 1.4	3.7 ± 1.0	7.8 ± 1.6	20.4 ± 4.1
Ontario (ON)	13 875 394	11.1 ± 1.9	4.4 ± 1.9	6.9 ± 2.2	22.3 ± 6.0
Quebec (QC)	8225 950	9.1 ± 2.7	3.2 ± 0.9	6.2 ± 1.4	18.5 ± 5.0
New Brunswick (NB)	763 350	6.3 ± 1.9	2.9 ± 1.4	7.1 ± 1.8	16.3 ± 5.0
Prince Edward Island (PEI)	146 969	9.2 ± 2.4	2.7 ± 0.8	5.5 ± 1.3	17.0 ± 4.5
Nova Scotia (NS)	942 790	7.6 ± 2.8	3.7 ± 1.9	6.2 ± 2.0	17.4 ± 6.7
Newfoundland and Labrador (NL)	529 426	7.3 ± 3.3	3.3 ± 1.2	6.1 ± 3.0	16.6 ± 7.4
Total	35 989 316	9.9 ± 2.2	4.3 ± 1.5	7.6 ± 2.0	21.8 ± 5.7

activity data, representative of the Canadian population. The average daily time spent in major locations by age groups and population-weighted average daily time spent in major locations for all Canadians are summarized in table 8. On average, Canadians spend 70% of the time indoors at home, and 19% of the time indoors other than at home. Outdoor activities including time in vehicles account for about 11% of the time.

Most people spend a large percentage of their time indoors where the building material acts as both a source of radioactivity and a shield. Indoor exposure to terrestrial gamma radiation is modified by the materials of construction and by the position of the individual within the structure. Wood, plastic, metal and glass have relatively little activity, while brick, concrete and other masonry material tend to be similar to soil in the surrounding area [22]. In this study, we follow the simple procedure adopted by the National Council on Radiation Protection (NCRP) [22] and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [19] which is to estimate the average indoor γ-ray dose from the outdoor terrestrial exposure rate using conversion factors.

Using the outside terrestrial values to derive inside values is based on the assumption that most building materials are of local origin. In Canada, the majority of single family dwellings have concrete floors or basements which are generally underlain by a thick gravel bed originating from a local quarry. In addition, the concrete itself is to a large extent composed of sand and gravel of local origin. Concrete is also the major building material for most apartment blocks or office buildings [3].

In estimating the ground gamma radiation levels inside a building, the shielding effects of the walls and the floors must also be considered. Similar to the housing characteristics in the US, most dwellings in Canada are wood-frame buildings. Therefore, the indoor-to-outdoor ratios (the building attenuation factors) recommended by the NCRP [22] are applied here, as given in table 9.

Data from Statistics Canada's 2016 Census [23] for the different types of dwellings that Canadians live in are summarized in table 10. The average population-weighted building attenuation factor is 0.854 for Canadian dwellings.

On average, Canadians spend a total of 6165 h indoor at home during a year. Considering the average building attenuation factor of 0.854, the annual average effective dose received indoor at home can be derived from the annual average outdoor γ-ray effective dose rate by multiplying the building attenuation factor and the total hours spent indoor at home. Results are given in the 4th column of table 11. The population-weighted annual average effective dose from exposure to terrestrial radiation indoors at home is estimated to be 115 ± 30 μSv in Canada.

For indoors away from home, i.e. in schools, workplace buildings or public facilities, the building attenuation factor is 0.9. The annual average effective dose received indoors away from home is the product of 1628 h, the building attenuation factor and the annual outdoor effective dose rate. Results are given in the 5th column of table 11. The population-weighted annual average effective dose from exposure to terrestrial radiation indoors away from home is estimated to be 31.9 ± 8.3 μSv in Canada.

Table 8. Daily time spent in major locations by age groups and population-weighted average daily time spent in major locations for all Canadians (daily percentages in brackets).

Age group	Population (2016 Census) [17]	Location	Mean time spent (hours)
Infants (<1 year)	383 216	Indoors at home	21.38 (89%)
		Indoors away from home	1.17 (5%)
		Outdoors	0.95 (4%)
		In vehicle	0.50 (2%)
Young children (1–4 years)	1559 575	Indoors at home	17.73 (74%)
		Indoors away from home	3.67 (15%)
		Outdoors	1.82 (8%)
		In vehicle	0.78 (3%)
Children (5–11 years)	2771 399	Indoors at home	17.12 (71%)
		Indoors away from home	4.27 (18%)
		Outdoors	1.80 (8%)
		In vehicle	0.81 (3%)
Adolescents (12–19 years)	3235 477	Indoors at home	16.67 (69%)
		Indoors away from home	4.98 (21%)
		Outdoors	1.48 (6%)
		In vehicle	0.87 (4%)
Adults (20–59 years)	19 925 692	Indoors at home	16.03 (67%)
		Indoors away from home	5.13 (21%)
		Outdoors	1.32 (6%)
		In vehicle	1.52 (6%)
Seniors (60+ years)	8234 128	Indoors at home	18.63 (78%)
		Indoors away from home	2.98 (12%)
		Outdoors	1.32 (6%)
		In vehicle	1.07 (4%)
Canadians	36 109 487	Indoors at home	16.89 (70%)
		Indoors away from home	4.46 (19%)
		Outdoors	1.39 (6%)
		In vehicle	1.26 (5%)

Table 9. Building attenuation factors (L_H) for typical constructions in North America [22].

Building category	L_H
Single-family detached	0.9
Single-family attached	0.9
Apartments 2–4 units	0.85
Apartments >5 units	0.7
Others: mobile home, recreational vehicle, boat	1.0
Schools, workplaces	0.9

Considering the average daily time of 1.39 h spent outdoors (a total of 507 h a year), the annual average outdoor effective doses from terrestrial radiation are calculated and presented in the 6th column of table 11. The population-weighted annual average outdoor effective dose from exposure to terrestrial radiation is estimated to be 11.0 $\pm$ 2.9 μSv in Canada.

Since metal and glass have relatively little activity and the attenuation factor for inside vehicles is 1.0, the annual average effective dose received inside vehicles is the product of 460 h and the outdoor effective dose rate. Results are given in the 7th column of table 11. The population-weighted annual average effective dose from exposure to terrestrial radiation inside vehicles is estimated to be 10.0 $\pm$ 2.6 μSv in Canada.

Table 10. Attenuation factors (L_H) for different building types in Canada.

Structural type of dwelling	Number of households	Number of person in households	L_H
Single-detached house	7541 495	20 748 070	0.9
Single-attached house	36 000	77 545	0.9
Semi-detached house	698 795	1880 600	0.9
Row house	891 305	2305 885	0.85
Apartment or flat in a duplex	784 300	1934 940	0.85
Apartment in a building that has fewer than five storeys	2539 390	4608 960	0.7
Apartment in a building that has five or more storeys	1391 040	2506 530	0.7
Movable dwelling (mobile homes, houseboats, recreational vehicles and railroad cars)	189 755	397 535	1.0
Total	14 072 080	34 460 065	0.854

Combining these four major locations, the estimated total average annual effective doses received by external exposure to terrestrial radiation vary from 126 ± 38 μSv in New Brunswick to 214 ± 61 μSv in British Columbia. The population-weighted annual effective dose from exposure to terrestrial gamma rays is 167 ± 43 μSv in southern Canada, excluding the northern territories. If we exclude the limited data from BC, the estimated total population-weighted annual average effective dose from exposure to terrestrial radiation is 160 ± 41 μSv in Canada.

6. Discussion

As shown in the map of annual outdoor effective dose from external radiation for Canada and the United States [4], exposure levels to terrestrial radiation vary geographically from less than 40 μSv y^{-1} to more than 1000 μSv y^{-1}. Based on AGRS data collected in the mid 1970s to support geological mapping and mineral exploration in areas of high mineral potential, Grasty *et al* [3] calculated that the population-weighted summer outdoor exposure rate from terrestrial gamma radiation was 32.2 ± 20.0 nGy h^{-1} (3.7 ± 2.3 μR h^{-1}). When considering attenuation of the airborne signal by forest cover, attenuation of the ground radiation by snow and effects of seasonal variations of soil moisture, the population-weighted outdoor exposure rate from terrestrial radiation was found to be 24.3 ± 14.8 nGy h^{-1} (2.8 ± 1.7 μR h^{-1}) in Canada averaged over an entire year. Using a conversion factor of 0.69 Sv Gy^{-1}, an average indoor-to-outdoor dose rate ratio of 1.08 and assuming 2 h of each day spent outdoors and 22 h indoors, the average annual effective dose from external gamma radiation was determined to be 210 ± 130 μSv (21 ± 13 mrem) [3]. The summer outdoor absorbed dose rate in air (32.2 ± 20.0 nGy h^{-1}) determined from the earlier AGRS surveys over largely unpopulated areas of Canada is lower than the value of 40.9 ± 10.6 nGy h^{-1} determined from GGRS surveys in populated areas reported here, but well within the observed variation range.

Considering different correction/conversion factors, different indoor-to-outdoor ratios and different time patterns applied in the earlier and current assessments, the population-weighted average annual effective dose from external gamma radiation of 167 ± 43 μSv determined from GGRS surveys from 2007 to 2010 in populated areas is in general agreement with the earlier assessments of 210 ± 130 μSv from AGRS surveys conducted in the mid 1970s and 219 ± 59 μSv from truck-borne radiometric survey on paved roads in four cities in the fall of 2002.

Prior to the NRP and NASGLP activities, most GGRS measurements were conducted to evaluate the application of AGRS surveys to bedrock mapping and mineral exploration. As such, most GGRS measurements were collected almost exclusively on bedrock exposures and would therefore have limited or reduced application to assessing the population-weighted annual external dose. Many such measurements would also have been from less populated areas of Canada. The NRP and NASGLP GGRS measurements were collected exclusively from surface soils located in more populated areas of southern Canada. The radioelement concentrations derived from these GGRS measurements may therefore be considered more representative of the external gamma exposure experienced by the majority of the Canadian population.

Table 11. Annual effective doses in four major locations and the total estimated from the annual outdoor absorbed dose rate.

Province	Population (2016 Census)	Annual outdoor effective dose rate nSv h^{-1}	E μSv indoor at home	E μSv indoors other than home	E μSv outdoor	E μSv in vehicle	E μSv Total
BC	4859250	27.8 ± 7.9	147 ± 41	40.8 ± 11.5	14.1 ± 4.0	12.8 ± 3.6	214 ± 61
AB	4196061	22.0 ± 3.4	116 ± 18	32.3 ± 5.0	11.2 ± 1.7	10.1 ± 1.6	170 ± 26
SK	1135987	23.6 ± 5.7	124 ± 30	34.6 ± 8.3	12.0 ± 2.9	10.9 ± 2.6	182 ± 44
MB	1314139	20.4 ± 4.1	107 ± 21	29.9 ± 6.0	10.3 ± 2.1	9.4 ± 1.9	157 ± 31
ON	13875394	22.3 ± 6.0	117 ± 31	32.7 ± 8.8	11.3 ± 3.0	10.3 ± 2.8	172 ± 46
QC	8225950	18.5 ± 5.0	97 ± 26	27.0 ± 7.4	9.4 ± 2.5	8.5 ± 2.3	142 ± 39
NB	763350	16.3 ± 5.0	86 ± 26	23.9 ± 7.3	8.3 ± 2.5	7.5 ± 2.3	126 ± 38
PEI	146969	17.0 ± 4.5	90 ± 23	25.0 ± 6.5	8.6 ± 2.3	7.8 ± 2.1	131 ± 34
NS	942790	17.4 ± 6.7	91 ± 35	25.5 ± 9.8	8.8 ± 3.4	8.0 ± 3.1	134 ± 52
NL	529426	16.6 ± 7.4	87 ± 39	24.3 ± 10.9	8.4 ± 3.8	7.6 ± 3.4	128 ± 57
Total	35989316	21.8 ± 5.7	115 ± 30	31.9 ± 8.3	11.0 ± 2.9	10.0 ± 2.6	167 ± 43

7. Conclusions

From the ground gamma radiometric survey (with a total of 1057 sites) conducted in the summer from 2007 to 2010 in populated areas across Canada, the population-weighted average radioelement concentrations in soil were found to be 1.40% for K, 1.47 ppm for eU and 5.70 ppm for eTh. The population-weighted average summer outdoor γ-ray absorbed dose rate in air at 1 m above ground was determined to be 40.9 $\pm$ 10.6 nGy h^{-1} in Canada. Of the 40.9 nGy h^{-1}, 45% originated from potassium, 35% from the thorium series, and 20% from the uranium series. When the effects of seasonal variations of soil moisture and the attenuation of the ground radiation by snow were considered, the population-weighted average annual outdoor exposure rate from terrestrial radiation was lowered to 30.6 $\pm$ 8.0 nGy h^{-1}. Considering the exposure outdoors and indoors in various types of buildings as well as exposure to radionuclides in building materials (assuming most building materials are of local origin), the population-weighted annual effective dose from exposure to terrestrial gamma rays was estimated to be 167 $\pm$ 43 μSv in southern Canada, excluding the northern territories. On average, Canadians spend 70% of their time indoors at home, 19% of their time indoors away from home, 6% of their time outdoors and 5% of their time in a vehicle. Under this time pattern, indoor exposures at home contribute 69% of the total annual effective dose, followed by 19% from indoors exposure other than at home, 6.2% from outdoor exposures and 5.8% from exposures inside vehicles. This assessment is in general agreement with earlier assessments based on airborne and truck-borne radiometric surveys.

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