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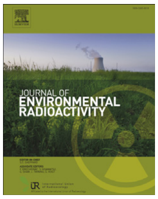

A study on the correlation between soil radon potential and average indoor radon potential in Canadian cities

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ABSTRACT

Exposure to indoor radon is identified as the main source of natural radiation exposure to the population. Since radon in homes originates mainly from soil gas radon, it is of public interest to study the correlation between radon in soil and radon indoors in different geographic locations. From 2007 to 2010, a total of 1070 sites were surveyed for soil gas radon and soil permeability. Among the sites surveyed, 430 sites were in 14 cities where indoor radon information is available from residential radon and thoron surveys conducted in recent years. It is observed that indoor radon potential (percentage of homes above 200 Bq m^{-3}; range from 1.5% to 42%) correlates reasonably well with soil radon potential (SRP: an index proportional to soil gas radon concentration and soil permeability; average SRP ranged from 8 to 26). In five cities where in-situ soil permeability was measured at more than 20 sites, a strong correlation ($R^2 = 0.68$ for linear regression and $R^2 = 0.81$ for non-linear regression) was observed between indoor radon potential and soil radon potential. This summary report shows that soil gas radon measurement is a practical and useful predictor of indoor radon potential in a geographic area, and may be useful for making decisions around prioritizing activities to manage population exposure and future land-use planning.

1. Introduction

Radon (^{222}Rn) is a naturally occurring radioactive gas generated by the decay of uranium bearing minerals in rocks and soils. A certain fraction of the radon escapes from the ground into the air. In the open air, radon is diluted to low concentrations and is not considered a health concern. However, radon that enters an enclosed space, such as a family house or a school building, can sometimes accumulate to concentrations above the Canadian Action Level (200 Bq m^{-3}). Soil gas radon contributing to the indoor environment has been identified as the main source of natural radiation exposure to the population (UNSCEAR, 2006). Radon has been identified as the second leading cause of lung cancer after tobacco smoking (WHO, 2009).

Soil gas radon measurement is a useful tool for the assessment of environmental radon potential and for the prediction of potential indoor radon concentrations in a geographic area, as demonstrated by many studies in various geographic locations (Keller et al., 1992; Mose et al., 1992; Neznal et al., 1996; Akerblom and Mellander, 1997; Vaupotic et al., 2002; Sundal et al., 2004; Reimer and Szarzi, 2005; Neznal et al., 2006; Kemski et al., 2006, 2009; Chen et al., 2009a; Minda et al., 2009; Barnet, 2012; Cinelli et al., 2015; Lara et al., 2015). Various studies have shown that in addition to radon levels in the soil, the soil permeability is another important factor in determining the radon potential of a site or an area, because higher permeability enables the increased migration of soil gas radon from soil into houses. For example, in a German case study in 1988–1989, Keller et al. found that high radon levels in the soil cause high indoor concentrations, if there are easy pathways into houses, and positive radon anomalies in the soil gas coincide with the locations of houses showing the highest concentrations (Keller et al., 1992). In northern Virginia and southern Maryland, Mose et al. attempted to predict which geographic areas should be associated with a high percentage of homes with unusually high indoor radon levels based on estimates of soil radon and soil permeability for geological units (Mose et al., 1992). They concluded that predictions of indoor radon based on estimates of home site soil radon and soil permeability are very useful. Similar conclusions were obtained in a recent study in Brazil (Lara et al.,

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2015) when using soil features to predict indoor radon concentration. Barnet (2012) compared two different methods (real and calculated) for evaluating the relationship of soil gas radon and probability of indoor radon exceeding 200 Bq m^{-3} based on data sets from the Czech Republic, the results showed minor differences.

Since radon in soil is believed to be the main source of radon in Canadian homes, it is of public interest to study the correlation between radon in soil and radon indoors in different geographic locations. Based on measurement data collected from various soil and indoor radon surveys in the past 7 years, a summary report on the correlation between soil radon potential and indoor radon potential in Canadian cities is presented here.

2. Methods

2.1. Soil radon and permeability measurements

Soil gas radon concentration was determined by measuring the radioactivity of soil gas samples taken from a depth of 80 cm below the ground surface (Radon VOS, 2007a). Because the boulder-rich nature of glacial tills made it difficult to reach the target depth at some sites, the sample depth was occasionally reduced to 60 cm. Samples of soil gas were collected using a 150 ml syringe. The soil gas samples were then introduced into ionisation chambers for measurement. Background control measurements of the ionization chambers were performed before sampling soil radon. An ionisation chamber was only used when its background reading was below 0.7 kBq m^{-3}, as instructed by the manufacturer (Radon VOS, 2007a). Soil radon concentrations measured below 1 kBq m^{-3} were excluded since any potential leakage during the soil gas sampling could result in a lower radon concentration. Therefore, the lowest measured value of soil gas radon was excluded in the calculation of the average radon concentration for a survey site.

The permeability of the soil is influenced by natural soil moisture, density, effective porosity, as well as other parameters. Although absolute soil moisture measurements were not conducted in the surveys, the influence of soil moisture was indirectly measured with the permeability. In situ permeability measurements were performed with RADON-JOK, an instrument manufactured in the Czech Republic (Radon VOS, 2007b), at a depth of 60–80 cm below the ground surface. The measurement is based on air withdrawal by means of negative pressure. The soil gas is pumped under constant pressure through a probe (the same probe as used for soil radon collecting) with a constant surface, an active area created in the head of the probe at 80-cm below the ground. The soil gas permeability was calculated based on Darcy's equation (Koorevaar et al., 1987). For sites having very low permeability, the in situ soil gas permeability measurement could potentially take hours to complete. In these cases, a limit value of $2\cdot10^{-14}$ m^2 was assumed.

Long-term monitoring of soil radon variations was conducted at two reference sites in Ottawa (Chen et al., 2009a), from thawing of the ground in the late spring to 1 day before the first snowfall in early winter. Results showed that during the normal field survey period from June to September in Canada, a single field survey with multiple measurements of soil gas radon concentrations at a depth of 60–80 cm could characterise the soil gas radon level of a site within a deviation of ±30%. All soil radon surveys summarised here were conducted from June to September.

All surveys followed well established protocol of the National Soil Radon Project, a Canadian add-on project to the North American Soil Geochemical Landscapes Project (GSC, 2009). Surveys were conducted on a dry day with a clear sky at least the previous evening. Within a city, soil gas radon and soil permeability measurements were conducted in community parks within residential areas. The soil survey sites were areas of about 10×10 m^2 in low-traffic areas of community parks and away from roads. For each site, generally two permeability and five soil gas radon measurements were performed with four probes at each corner and one probe in the centre of the 10×10 m^2 survey area.

The soil radon potential (SRP) index is defined as, SRP $= (C - C_0) / (-\log(P) + \log(P_0))$ where C is the radon concentration of the soil gas in kBq m^{-3}, and P is the soil permeability in m^2. C_0 and P_0 are set to be 1 kBq m^{-3} and $1\cdot10^{-10}$ m^2, respectively (Neznal et al., 1996, 2006). The SRP is proportional to the radon concentration in soil. It depends also on soil gas permeability; the more permeable the soil, the higher is the SRP. Due to the extremely wide range of soil gas permeability over several orders of magnitude, the SRP is adjusted with the logarithm of soil permeability.

2.2. Indoor radon measurements

In order to assess thoron (^{220}Rn) contribution to indoor radon and thoron exposure combined, simultaneous radon and thoron measurements were first conducted in Ottawa, Winnipeg, Halifax and Fredericton (Chen et al., 2008a, 2009b, 2011). In 2014, a nationwide survey of residential radon and thoron concentrations was completed in 33 cities (accounting for approximately 70% of the Canadian population), with a sample size of roughly 4000 homes (Chen et al., 2015). In order for the result to be indicative of the average annual radon and thoron exposure, all tests were conducted for a period of at least three months in the typical heating season that runs from October to April. A passive integrated radon–thoron discriminative detector developed at the National Institute of Radiological Sciences in Japan (commercially known as RADUET) was used in these surveys. These results serve as the main data source of indoor radon concentrations in this summary report.

To gain a better understanding of radon concentrations in homes across Canada, a national residential radon survey was launched in April 2007. The survey used alpha track detectors, and conducted long-term (3-months or longer) radon measurements in roughly 14,000 homes in 121 health regions (administrative areas defined by the provincial ministries of health) across Canada (Health Canada, 2012). Results of this survey were added to the results from the above-mentioned city-based radon/thoron surveys when health region boundaries approximately matched the boundaries of cities considered here.

All surveys confirmed that radon was present in all homes in varying concentrations. The indoor radon concentrations varied widely in a geographic area. Even though it is hard to predict indoor radon concentration for any given house in a community, the average characteristics of indoor radon distribution should be representative for a geographic area. All surveys confirmed that indoor radon concentrations in a community followed log-normal distribution. A log-normal distribution is a two-parameter distribution characterised with the geometric mean (GM) and geometric standard deviation (GSD). Indoor radon potential of a geographic area or a city should be a quantity representing the characteristics of the two-parameter distribution of indoor radon concentrations in that area. Therefore, the percentage of homes above the Canadian Action Level of 200 Bq m^{-3} was chosen as the indicator of indoor radon potential for an area.

3. Results and discussion

From 2007 to 2010, a total of 1070 sites were surveyed for soil gas radon (Chen et al., 2008b, 2009c, 2012; Ford and Chen, 2008; Goodwin et al., 2009, 2010; Ford et al., 2010, 2015; Friske et al., 2012, 2013), as shown in Fig. 1. Among the sites surveyed, 476 sites were in cities where data could be correlated with indoor

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