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Methodology developed to make the Quebec indoor radon potential map

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HIGHLIGHTS

- 5 radiogeochemical datasets were used to map the geogenic indoor radon potential.
- An indoor radon potential was determined for each criterion using ANOVA.
- A combined indoor radon potential was determined and mapped.
- The radon potential based on indoor radon measurements only was mapped.
- The two maps were compared to validate the predicted geogenic radon potential.

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ABSTRACT

This paper presents a relevant approach to predict the indoor radon potential based on the combination of the radiogeochemical data and the indoor radon measurements in the Quebec province territory (Canada). The Quebec ministry of health asked for such a map to identify the radon-prone areas to manage the risk for the population related to indoor radon exposure. Three radiogeochemical criteria including (1) equivalent uranium (eU) concentration from airborne surface gamma-ray surveys, (2) uranium concentration measurements in sediments, (3) bedrock and surficial geology were combined with 3082 basement radon concentration measurements to identify the radon-prone areas. It was shown that it is possible to determine thresholds for the three criteria that implied statistically significant different levels of radon potential using Kruskal–Wallis one way analyses of variance by ranks. The three discretized radiogeochemical datasets were combined into a total predicted radon potential that sampled 98% of the studied area. The combination process was also based on Kruskal–Wallis one way ANOVA. Four statistically significant different predicted radon potential levels were created: low, medium, high and very high. Respectively 10 and 13% of the dwellings exceed the Canadian radon guideline of 200 Bq/m^3 in low and medium predicted radon potentials. These proportions rise up to 22 and 45% respectively for high and very high predicted radon potentials.
This predictive map of indoor radon potential based on the radiogeochemical data was validated using a map of confirmed radon exposure in homes based on the basement radon measurements. It was shown that the map of predicted radon potential based on the radiogeochemical data was reliable to identify radon-prone areas even in zones where no indoor radon measurement exists.

1. Introduction

In the last decades, studies showed that radon and its decay products are carcinogenic to humans and were classed as a group 1 substance (IARC, 1988). Alpha particles emitted from radon gas and its solid decay products are the second leading cause of lung cancer after tobacco smoking (WHO, 2009). Many countries developed maps of radon-prone areas to manage the exposure of their population to high indoor radon concentrations (Alexander and Devocelle, 1997; Appleton and Miles, 2010; Apte et al., 1999; Ball and Miles, 1993; Barnet et al., 2006; Doyle et al., 1990; Gundersen and Schumann, 1996; Heincke et al., 2008; Kemski et al., 2008; Lévesque et al., 1995; Martel, 1991; Savard et al., 1998; Skeppström and Olofsson, 2006; Smethurst et al., 2008; USEPA, 1993). After Health Canada lowered the Canadian radon guideline from 800 to 200 Bq/m^3 in 2007 (Health Canada, 2007), an Action plan about radon was prepared by the Quebec intersectorial radon committee. Mapping the radon-prone areas all over the Quebec territory was one of the main objectives of this Action plan. This new tool would help public health authorities identify populations living in zones with potentially high indoor radon levels and determine uniform and integrated management strategies.

There are two distinct approaches to map radon-prone areas: 1) maps based on direct indoor radon concentrations and 2) maps

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based on geological information relevant to radon (Miles, 1998). Because Quebec is a vast territory with sparsely populated regions, the indoor radon concentration coverage is not uniform. There are many areas with nonexistent or limited indoor radon measurements. Mapping the radon-prone areas for the entire province of Quebec was done by combining radiogeochemical measurements and indoor radon concentration measurements. The radiogeochemical data selected to map radon-prone areas were based on their availabilities and their redundancies in international studies: (1) equivalent uranium (eU) concentration from airborne surface gamma-ray measurements, (2) geochemistry (uranium concentration in sediment samples), and (3) geology (bedrock units and surficial deposits) (Drolet, 2011). Drolet et al. (2013) showed that there are positive proportion relationships (PPR) between the radiogeochemical measurements and the basement radon concentration measurements. They also showed that those PPR along with statistical studies are efficient to determine a radon potential based on each criterion individually.

The objective of this paper is to create a map having four different levels of radon potential (low, moderate, high and very high) based on the combination of the individual radon potentials calculated from the three above radiogeochemical criteria. The combination methodology is a statistical approach that uses Kruskal–Wallis one way analyses of variance by ranks (ANOVA). The paper also presents a validation of the thresholds set for the radiogeochemical data relevant to indoor radon levels and a combination methodology of these radiogeochemical data into a map of predicted radon potential.

2. Material and methods

2.1. Material

2.1.1. Existing methodologies to map radon-prone areas

Maps of radon-prone areas based on geological information relevant to radon have been developed in many countries and were made following different methodologies. Some use correlations between geological surveys and indoor radon concentrations (Appleton et al., 2011; Barnet et al., 2006; Chen et al., 2011; Doyle et al., 1990; Friedmann and Gröller, 2010; Garcia-Talavera et al., 2013; Gruber et al., 2013; Heincke et al., 2008; Ielsch et al., 2010; Kemski et al., 1992, 2001, 2008; Miles and Appleton, 2005; Savard et al., 1998; Smethurst et al., 2008; Verdoya et al., 2009; Wattananikorn et al., 2008). Authors set thresholds on radon-related variables (uranium concentrations in soils and rocks, equivalent uranium concentrations from gamma-ray surveys, soil gas radon measurements, percentages of dwellings that exceed the action level and building characteristics) to estimate levels of radon emission potential. Another radon potential mapping methodology is based on a multi-factor scoring system (Chen, 2009; Gundersen and Schumann, 1996; Skeppström and Olofsson, 2006; USEPA, 1993). Again, thresholds are set for radiogeochemical surveys and a scoring system is determined for each criterion. Summing the points attributed to each criterion gives a total score that is discretized into final radon potential categories. The multi-factor scoring system methodology was not applicable to map Quebec radon-prone areas because it is not effective when only one criterion is available in a territory (Chen, 2009) like it is the case in the highly populated Montréal and Laval regions where only the geology criterion is available.

2.1.2. Available datasets

The datasets are made of: (1) basement radon concentrations, (2) equivalent uranium (eU) concentrations from surface gamma-ray measurements, (3) uranium concentrations in sediments, (4) bedrock units and (5) surficial deposits. The basement radon measurements dataset totalizes 3082 data from the Quebec Ministry of Health and Social Services partners including Quebec Lung Association (QLA) (63%) and Health Canada (37%) (Fig. 1).

Positive proportion relationships were established between radiogeochemical measurements and 1417 basement radon concentration measurements conducted in Quebec (Drolet et al., 2013). Equivalent uranium concentrations from surface gamma-ray measurements, uranium concentrations interpolated from geochemical surveys and the geology criterion were discretized into statistically similar groups. Kruskal–Wallis one way ANOVA (with a p-value of 0.05) on basement radon concentrations within each class were used to calculate thresholds that indicate different levels of radon potential. Equivalent uranium concentrations from airborne surface gamma-ray measurements were discretized into three groups while uranium concentrations interpolated from geochemical surveys and the geology were discretized into two groups (Table 1).

Statistical calculations were made on basement radon concentration measurements within each group. Medians, 25th and 75th percentiles, geometric means and percentages of dwellings exceeding the three North American radon guidelines (150, 200 and 800 Bq/m^3) increase from the first to the last row of Table 1. Groups in the first row implied the lowest radon potential while those in the second row, a higher radon potential level. The gamma-ray spectrometry criterion $\geq$ 1.25 ppm has the highest radon potential. The methodology that combines the radon potential from each criterion into a total radon potential is presented herein.

2.2. Methods

2.2.1. Validation of the thresholds set for each discretized criterion

The thresholds limiting the statistically different groups were determined by calculating p-values with Kruskal–Wallis one way ANOVA by ranks. The hypothesis that the compared groups shared a common basement radon concentration mean can be rejected at the 95% confidence level when a p-value lower than 0.05 was calculated. Those p-values were calculated from the basement radon concentration dataset that included 3082 indoor radon measurements.

2.2.2. Combination of the radon potentials based on the three criteria

The information for the three radiogeochemical criteria was extracted for each of the 3082 basement radon concentration measurements using ESRI's ArcGIS 10.0 (ESRI, 2012). Table 2 shows the possible groups for the three criteria. A “No data” group was added for the airborne gamma-ray spectrometry and the geochemistry criteria because these predictors do not cover entirely the Quebec territory contrary to the geology criterion. By adding a “No data” value to the gamma-ray spectrometry and geochemistry criteria, all the three criteria have a possible value at each cell in the studied area. The size of the cells is inhomogeneous between the three criteria. The uranium concentrations in sediment dataset are made of a 100 m × 100 m grid and the bedrock unit dataset of a 40 m × 40 m grid. The eU concentrations from surface gamma-ray measurement dataset are made of multiple surveys having their grid sizes ranging from 25 m × 25 m to 1 km × 1 km. Non-dimensional values (0–1–2–N.D.) were also associated to each group as a simplification. For example, a basement radon concentration occurring in a region where there is a gamma-ray concentration of 2 ppm in equivalent uranium (“$\geq$1.25 ppm of eU” group), with non-existing interpolated geochemical data (“No data” group) and over a uranium-rich bedrock unit not confined by a silt/clay barrier (“Radon-prone units” group) was associated to non-dimensional values 2, N.D., and 1. Having four airborne gamma-ray spectrometry groups, four geochemistry groups and two geology groups, there are 32 possible scenarios. Powers of two values (2^n where n is a non-negative integer ranging from 0 to 9 herein) were also attributed to each group (Table 2). Summing the powers of two related to each scenario leads to 32 unique summations ranging from 273 to 648 (Table 3). Previous example (2–N.D.–1) could be expressed as 4–128–512 in terms of powers of two and would represent scenario 644 ($4 + 128 + 512 = 644$).