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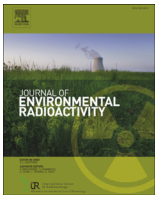

Distance to faults as a proxy for radon gas concentration in dwellings

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This research was done to demonstrate the usefulness of the local structural geology characteristics to predict indoor radon concentrations. The presence of geologic faults near dwellings increases the vulnerability of the dwellings to elevated indoor radon by providing favorable pathways from the source uranium-rich bedrock units to the surface. Kruskal–Wallis one-way analyses of variance by ranks were used to determine the distance where faults have statistically significant influence on indoor radon concentrations. The great-circle distance between the 640 spatially referenced basement radon concentration measurements and the nearest fault was calculated using the Haversine formula and the spherical law of cosines. It was shown that dwellings located less than 150 m from a major fault had a higher radon potential. The 150 m threshold was determined using Kruskal–Wallis ANOVA on: (1) all the basement radon measurements dataset and; (2) the basement radon measurements located on uranium-rich bedrock units only. The results indicated that 22.8% of the dwellings located less than 150 m from a fault exceeded the Canadian radon guideline of 200 Bq/m^3 when using all the basement radon measurements dataset. This percentage fell to 15.2% for the dwellings located between 150 m and 700 m from a fault. When using only the basement radon measurements located on uranium-rich bedrock units, these percentages were 30.7% (0–150 m) and 17.5% (150 m–700 m). The assessment and management of risk can be improved where structural geology characteristics base maps are available by using this proxy indicator.

1. Introduction

Radon is one of the six noble gases that occur naturally. Radon-222 (^{222}Rn), the most stable radon isotope, is an indirect radioactive product of uranium-238 (^{238}U). Consequently, the main sources of radon are the underlying rocks and soils (Borgoni et al., 2011; Hunter et al., 2009; IARC, 1988; Kochis and Leavitt, 1997; Nazaroff and Nero, 1988; Wattananikorn et al., 2008; Zhu et al., 1998). The alpha-particles emitted from the decaying of radon and its progenies represent the most important human exposure to ionizing radiation from environmental source (Cosma et al., 2013; Genay et al., 2006; Hauri et al., 2013). Epidemiological studies concluded that ^{222}Rn and some of its daughter elements (especially polonium-218 and polonium-214) are a major risk for lung cancer (Bochicchio, 2005; Darby et al., 2006) and are considered the second leading cause of lung cancer after tobacco smoking (WHO, 2009). Turner et al. (2011) noted a significant positive linear trend between lung cancer mortality and the categories of radon concentrations ($p = 0.02$) from the data of the American Cancer Society Cancer Prevention Study-II (CPS-II) prospective cohort. A 15% (95% confidence interval 1–31%) increase in the risk to die from lung cancer per each 100 Bq/m^3 radon was also observed. The 5-year survival rate for lung cancer is less than 20% (CCS, 2014).

In Canada, approximately 3261 cases of lung cancer are attributable to high indoor radon concentration exposure annually (Chen et al., 2012). Canadian public health authorities asked for maps of the radon potential to limit the radon exposure of its population. British Columbia (Branion-Calles et al., 2015; Rauch and Henderson, 2013), Ontario (Ford et al., 2014) and Nova Scotia (O'Reilly et al., 2013) prepared such radon risk maps along with a cross-Canada residential radon survey that collected approximately 14,000 indoor radon measurements (Health Canada, 2012; mapped in Hystad et al., 2014). In the Province of Quebec, an *Action plan about radon* was prepared by the Quebec intersectorial radon committee (QIRC). Effective in 2008, the main objectives were to develop a geogenic map of the radon potential for the Province of Quebec, to use the map as a preventive tool and to sensitize its population to the risk of high indoor radon concentration exposure. Drolet et al.

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(2013) established positive proportion relationships between the bedrock units, the quaternary sediment deposits at the surface, the equivalent uranium concentrations from surface gamma-ray measurements, the uranium concentrations interpolated from geochemical surveys in sediments and 1417 basement radon concentration measurements in Quebec. The Quebec map of the radon potential based on radiogeochemical data was created using these relationships (Drolet et al., 2014).

This provincial-scale study was conducted to highlight radon-prone areas based on large scale predictors. The present paper focuses on the relevance of using local structural geology characteristics as complementary data to improve the radon potential map (prone areas). The research assumption is that using such complementary data should enhance the effectiveness of the predicted radon concentration in dwellings.

2. Material and methods

2.1. Available datasets

Four datasets were used: (1) major faults location, (2) bedrock units, (3) quaternary surficial deposits and (4) basement radon concentration measurements. The available airborne gamma-ray measurements of equivalent uranium concentration within the first 30 cm of earth surface and the uranium concentrations from geochemical surveys in lake and water course sediments were not included in this study because they are surficial surveys. The objectives of this study is to determine the relationships between indoor radon concentrations and the presence (or not) of a fault in the vicinity of the radon measurement points within or without uranium-rich bedrock units. The uranium surficial surveys mentioned above are not relevant for the study presented herein.

Both the fault locations and the bedrock unit base maps are available on SIGEOM, a georeferenced geoscientific database provided by the Ministère de l'Énergie et des Ressources naturelles of Québec. The surficial sediments base map is a combination of nine Quaternary geological maps (Dredge, 1983; Lamarche, 2011; Lasalle and Tremblay, 1978; Parent, 2014; St-Onge, 2009; Veillette, 1996; Veillette and Cloutier, 1993, 2014; Veillette et al., 2003). The basement radon concentration dataset was made of 3983 measurements from the ministère de la Santé et des Services sociaux (MSSS) (Fig. 1). This dataset is made of 3374 basement radon measurements performed by homeowners who asked for a radon test in their dwelling on a voluntary basis that was compiled by the Quebec Lung Association (QLA). Health Canada randomly sampled the other 609 dwellings all around the Province of Quebec for their basement radon concentrations. The basement radon concentrations were preferred than the measurements on other dwelling levels because they are generally higher and represent a worst case scenario. The radon concentrations in basements are also more directly related to the radon concentrations in the soil and bedrock that surrounds the dwellings foundations. The rate at which radon gas is diluted from basement to other floor levels is not necessarily constant depending on external factors such as the type of house and the indoor/outdoor air exchange. Using only the basement radon measurements ensures a more homogeneous dataset. These basement radon concentration measurements in dwellings are sparsely distributed over the entire province but show a higher density in highly populated areas such as Montréal, Québec City and Gatineau areas. The addresses of the basement radon measurements were geo-referenced using the G.O.LOC tool (Gestion des opérations de localisation et de cartographie). G.O.LOC. is a free application of the ministère de la Sécurité publique du Québec (MSP) that accurately transforms the input addresses into geographic coordinates.

2.2. Methodology

2.2.1. Calculation of the great-circle distances

The study was restricted to areas where the density of radon measurements was significant on an extended area and where detailed geological information including structural geology data were available. The objective was to verify if a correlation exists between radon gas concentrations in the basement of dwellings and distance to existing faults. The Communauté métropolitaine de Montréal (CMM) and the Communauté métropolitaine de Québec (CMQ) were the selected areas because they are the most populated of the Province of Quebec and have both the above cited selection criteria. The numerous measurements ensured that the distances between the faults and the basement radon measurements covered a wide range of values and were then statistically reliable. Having many measurements points in the vicinity of faults and also far from them strengthen the statistical robustness of the established relationships. The Gatineau area is a highly populated municipality that could have been included in the study, but most of the basement radon measurements in this zone are far from major faults. Also, there are not many uranium-rich bedrock units in the Gatineau area, so it was not relevant to add these data in the study. However, the basement radon measurements in the Gatineau area were used as a validation dataset to test the approach for the non-uranium-rich bedrock units.

The basement radon concentration measurements were superimposed on major faults identified on the geological base map using the ESRI's ArcGIS 10.1 environment (ESRI, 2012). The distance from the basement radon measurement point to the nearest fault was calculated using the NEAR function (Fig. 2). The distances calculated by this function are in the same units as the coordinate system of the input features (major fault location and basement radon concentration measurements). Using a geographic coordinate system leads to a calculated NEAR distance in decimal degrees (as opposed to linear units). However, the geographic coordinate system (NAD 1983) was chosen for the input datasets because they cover a large area. A projected coordinate system might involve distortion at large scale (Natural Resources Canada, 2014), so the calculated distance between the basement radon measurement points and the nearest fault might be erroneous. The ArcGIS NEAR function has the option to identify where in the fault polyline is the nearest coordinates to the basement radon measurements point.

The great-circle distances between the basement radon measurement points and the nearest fault point identified from the ArcGIS NEAR function were calculated from the modified Haversine formula (Eqs. (1) and (2)) (Robusto, 1957; Seema and Sheema, 2009) and the spherical law of cosines (Eq. (3)) (Chen et al., 2004). These equations assume a spherical earth and ignore the ellipsoidal effects, but are accurate approximations to calculate the distance between two points on earth knowing their coordinates.

$$D_{HAVERSINE} = 2R * a\,tan2\left(\sqrt{a},\ \sqrt{1-a}\right) \qquad \text{(Eq. 1)}$$

with $$a = sin^2\left(\frac{\varnothing_2 - \varnothing_1}{2}\right) + cos\,(\varnothing_1)\,cos(\varnothing_2)\,sin^2\left(\frac{\lambda_2 - \lambda_1}{2}\right) \qquad \text{(Eq. 2)}$$

$$D_{COSINES} = R{*}cos^{-1}[sin(\varnothing_1)\,sin(\varnothing_2) + cos(\varnothing_1)\,cos(\varnothing_2)\,cos(\lambda_2 - \lambda_1)] \qquad \text{(Eq. 3)}$$

where D: distance between two points at the surface of earth (in m)

R: radius of the sphere