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Indoor radon measurements in south west England explained by topsoil and stream sediment geochemistry, airborne gamma-ray spectroscopy and geology

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ABSTRACT

Predictive mapping of indoor radon potential often requires the use of additional datasets. A range of geological, geochemical and geophysical data may be considered, either individually or in combination.

The present work is an evaluation of how much of the indoor radon variation in south west England can be explained by four different datasets: a) the geology (G), b) the airborne gamma-ray spectroscopy (AGR), c) the geochemistry of topsoil (TSG) and d) the geochemistry of stream sediments (SSG). The study area was chosen since it provides a large (197,464) indoor radon dataset in association with the above information.

Geology provides information on the distribution of the materials that may contribute to radon release while the latter three items provide more direct observations on the distributions of the radionuclide elements uranium (U), thorium (Th) and potassium (K). In addition, (c) and (d) provide multi-element assessments of geochemistry which are also included in this study.

The effectiveness of datasets for predicting the existing indoor radon data is assessed through the level (the higher the better) of explained variation (% of variance or ANOVA) obtained from the tested models. A multiple linear regression using a compositional data (CODA) approach is carried out to obtain the required measure of determination for each analysis.

Results show that, amongst the four tested datasets, the soil geochemistry (TSG, i.e. including all the available 41 elements, 10 major – Al, Ca, Fe, K, Mg, Mn, Na, P, Si, Ti - plus 31 trace) provides the highest explained variation of indoor radon (about 40%); more than double the value provided by U alone (ca. 15%), or the sub composition U, Th, K (ca. 16%) from the same TSG data. The remaining three datasets provide values ranging from about 27% to 32.5%. The enhanced prediction of the AGR model relative to the U, Th, K in soils suggests that the AGR signal captures more than just the U, Th and K content in the soil.

The best result is obtained by including the soil geochemistry with geology and AGR (TSG + G + AGR, ca. 47%). However, adding G and AGR to the TSG model only slightly improves the prediction (ca. +7%), suggesting that the geochemistry of soils already contain most of the information given by geology and airborne datasets together, at least with regard to the explanation of indoor radon.

From the present analysis performed in the SW of England, it may be concluded that each one of the four datasets is likely to be useful for radon mapping purposes, whether alone or in combination with others. The present work also suggest that the complete soil geochemistry dataset (TSG) is more effective for indoor radon modelling than using just the U (+Th, K) concentration in soil.

1. Introduction

Radon (^{222}Rn) is a geogenic radioactive gas permanently produced in all rocks and soils by radioactive decay of radium (^{226}Ra),

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which primarily derives from uranium (^{238}U). However uranium levels tend to vary with rock type, with higher Rn production being observed in uranium (and/or radium)-rich rocks, as expected. High concentrations of U (and/or Ra) can be found in rocks such as, uranium ores, some granites, black shales, some sandstones, phosphate rocks, some limestones and U (and/or Ra)-rich soils (e.g., over some limestones) (Appleton, 2013). In general, locations overlying rocks containing high levels of uranium show higher radon potential than those overlying rocks with low levels of U. Radon gas released from rocks and soils reaches open air, and rapidly disperses in the atmosphere to average levels of 4 Bq. m^{-3} (HPA , 2010). As a consequence, radon typically becomes a health risk only in confined areas, where it tends to accumulate, such as in underground caves and mines, as well as inside houses and other buildings. Radon from the ground can enter houses through gaps and cracks in the floor, walls and pipes mainly due to differential indoor - outdoor – soil air conditions (pressure and temperature) (Appleton, 2013). As radon is a heavy noble gas, it tends to sink and has the potential to concentrate further in poorly ventilated basements and cellars. In the UK, the average indoor radon concentration is 20 Bq. m^{-3} (ranging from less than 10 Bq. m^{-3} to over 17,000 Bq. m^{-3}) and thus is 10 times lower than the 200 Bq. m^{-3} Action Level established for indoor radon in the UK (NRPB, 1990). Radon concentration in the soil pore space is quite variable, ranging from less than 1 to more than 2500 kBq.m^{-3} (Appleton, 2013), thus it is generally 1 to 3 orders of magnitude higher than in the air above the ground, both indoor and outdoor (Varley and Flowers, 1998). In addition to the rock and soil capacity for radon gas production, other ground characteristics, such as permeability, water content, organic matter or proximity to faults, as well as the weather conditions, temperature, pressure and precipitation, are among the factors to be considered in order to account for the radon concentration in soil.

Despite of other relevant factors (atmospheric conditions, construction of the building, lifestyle including heating and ventilation routines) contributing to radon levels inside houses, geology is the most important one, as it is the source. According to Appleton and Miles (2010) approximately 25% of the total variation of indoor radon in England and Wales can be explained by the geology. Hunter et al. (2009) found that geology, at 19.7%, is the most important factor explaining the variance of UK indoor radon, while less than half (8.9%) was attributed to the sum of seven house-related factors, including, house type (3.8%), double-glazing (2.3%), date of building (1.1%), floor level (1.0%), floor type (0.5%), ownership (0.1%) and draught proofing (0.1%).

1.1. *Radon mapping*

The dependence of indoor radon on the geology has led to the development of radon mapping methods that use geological maps together with indoor radon measurements. Other proxies, such as Rn concentration in the soil gas; U (and Ra) content measured in rock, soil or stream sediment; the U content estimated from ground or airborne Gamma-Ray spectroscopy; soil/rock permeability data, or proximity to faults are also used for the assignment of a radon potential classes (Appleton, 2013). Often, the proxies are used according to their availability. Relative to the other mentioned proxies, indoor radon measurements have the advantage of being directly related to the space where people spend most of their time (i.e. home and other buildings). Typically, the indoor radon measurements are spatially very unevenly distributed, clustered in highly populated areas and rare or absent in rural areas. This can be partially overcome by using the geology to extend the trends to areas with sparse or absent indoor data. Nevertheless, it may constitute a drawback for large areas with no human occupation at present, but which may be planned for the near future. In fact, the implementation of radon preventative measures in new buildings on radon prone areas (e.g., in the UK), will, over time, induce an artificial reduction of the estimated radon potential, in case this is based on indoor radon measurements.

In the UK, Public Health England (PHE) and the British Geological Survey (BGS) collaborate in the production of radon potential maps; these information have already been released for England and Wales (Miles et al., 2007), for Scotland (Miles et al., 2011) and for Northern Ireland with the collaboration of the Geological Survey Northern Ireland (Daraktchieva et al., 2015). Digital geological information (DiGMapGB-50k, mostly at 1:50,000 scale, http://www.bgs.ac.uk/products/digitalmaps/DiGMapGB_50.html), is used together with the indoor radon measurements for mapping the radon risk. The bedrock and the superficial 1:50,000 scale units are simplified (by age and lithology, or permeability and genetic type respectively) to produce a new set of codes, which are then combined together in a bedrock-superficial parent material (**BS**, geological combination) polygon code. Finally, the **BS** polygons are intercepted with the British National Grid (BNG) 1 km grid squares, resulting in the **KM1BS** polygons which constitute the basic mapping units. The following steps of the UK radon mapping methodology are performed after allocating each indoor radon measurement to the **KM1BS** polygon underlying it. The radon potential is then computed for each basic polygon (**KM1BS**) using the nearest data and provided that it belongs to same geological combination (**BS**). After mapping each **BS** separately, these are assembled in a final map. This radon potential map provides an estimation of the probability of homes in the UK having radon concentrations above the UK Action Level (200 Bq. m^{-3}). Further explanation about the UK radon mapping method and main results can be found in Miles and Appleton (2005), Miles et al. (2007, 2011) and Daraktchieva et al. (2015).

This paper is a contribution to the European Geogenic Radon Potential/Natural Radiation mapping project, led by the Joint Research Centre (JRC) of the European Commission. JRC started to design a European map of the geogenic radon potential exploring different approaches used by different European countries for development of national radon risk maps. A general classification scheme applicable to all countries is under development, which reflects the different experiences and type of information used at national level. Datasets including key variables such as indoor radon, geology, soil gas radon, U (and Ra) concentrations in soil and bedrock, airborne gamma-ray data, terrestrial gamma dose rate and permeability, seem to be the most obvious and appropriate approach.

The main question addressed in the present work is to what extent **geology (G)**, **airborne gamma-ray spectroscopy (AGR)**, **topsoil geochemistry (TSG)** and the **stream sediment geochemistry (SSG)** are able to explain the **indoor radon** variation, and based on the results, to assess the usefulness of these proxies for geogenic radon mapping. The above parameters are tested on the radon prone area of SW England, which is one of the most tested areas for indoor radon in the world.

2. Materials and methods

2.1. *Geology and the KM1BS polygons*

The geology of SW England, as shown in Fig. 1, mainly consists of a range of metasediments deposited in palaeo sedimentary basins during the Devonian and the Carboniferous, to which followed the granite intrusion of the prominent Cornubian batholith, emplaced in the later stages of the Variscan orogeny, Late Carboniferous to Early Permian (see Kirkwood et al., 2016 and references herein).

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