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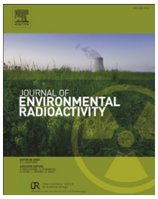

The use of mapped geology as a predictor of radon potential in Norway

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Radon exposure is considered to cause several hundred fatalities from lung-cancer each year in Norway. A national map identifying areas which are likely to be exposed to elevated radon concentrations would be a useful tool for decision-making authorities, and would be particularly important in areas where only few indoor radon measurements exist. An earlier Norwegian study (Smethurst et al. 2008) produced radon hazard maps by examining the relationship between airborne gamma-ray spectrometry, bedrock and drift geology, and indoor radon. The study was limited to the Oslo region where substantial indoor radon and airborne equivalent uranium datasets were available, and did not attempt to test the statistical significance of relationships, or to quantify the confidence of its predictions. While it can be anticipated that airborne measurements may have useful predictive power for indoor radon, airborne measurement coverage in Norway is at present sparse; to provide national coverage of radon hazard estimates, a good understanding of the relationship between geology and indoor radon is therefore important. In this work we use a new enlarged ($n = 34{,}563$) form of the indoor radon dataset with national coverage, and we use it to examine the relationship between geology and indoor radon concentrations. We use this relationship to characterise geological classes by their radon potential, and we produce a national radon hazard map which includes confidence limits on the likelihood of areas having elevated radon concentrations, and which covers the whole of mainland Norway, even areas where little or no indoor radon data are available. We find that bedrock and drift geology classes can account for around 40% of the total observed variation in radon potential. We test geology-based predictions of RP (radon potential) against locally-derived estimates of RP, and produce classification matrices with kappa values in the range 0.37–0.56. Our classifier has high predictive value but suffers from low sensitivities for radon affected areas. We investigate an alternative classification method based on a Naïve Bayes classifier which results in similar overall performance. The work forms part of an ongoing study which will eventually incorporate airborne equivalent uranium data, as and when new airborne data become available.

1. Introduction

Radon (radon-222) is a colourless and odourless radioactive gas formed by the decay of radium-226, which is part of the naturally-occurring uranium-238 decay series, and which is present in many rocks and minerals. Radon is the second largest cause of lung cancer after smoking (WHO, 2009) and is estimated to account for around 2% of all cancer deaths in Europe (Darby et al., 2005, 2006).

In common with other radiation authorities, the Norwegian Radiation Protection Authority (NRPA) have established recommended upper limits for radon concentrations in homes: concentrations should not exceed 200 Bq/m^3 (*maximum limit*), and homes where concentrations exceed 100 Bq/m^3 (*action limit*) should be considered for radon-reducing measures, where practical (Statens strålevern 2009). In Norway such high radon concentrations are not unusual, with average indoor radon concentrations not far under the action limit of 100 Bq/m^3; concentrations as high as several thousand Bq/m^3 are not unknown (Strand et al., 2003).

The amount of radon entering a home is a complex function of many variables including geology, building style, building materials, meteorological conditions, and the lifestyle of the inhabitants

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(Nazaroff, 1992; Robinson et al., 1997; Miles, 2001; Mäkeläinen et al., 2001; Borgoni et al., 2014). The origin of most indoor radon however is the geology under and around buildings, where uranium-bearing rocks and deposits provide a source of radon gas, and where transport to the surface may be facilitated by permeable superficial deposits. In Norway, particularly high radium concentrations in alum shale rocks – up to several thousand Bq/kg (Nordic, 2000) – are known to be associated with elevated indoor radon concentrations (Stranden and Strand, 1988), and some granites may contain up to several hundred Bq/kg radium-226 (Nordic, 2000).

A national map identifying areas prone to elevated indoor radon concentrations would be an important planning aid to local authorities, particularly in areas where only few indoor radon data exist. Such a product would also help in raising awareness of potential radon problems and encouraging homeowners to carry out radon measurements and radon mitigation measures as appropriate.

Approaches to radon hazard assessment have included direct measurements of indoor radon (Dubois, 2005), soil gas measurements (Kemski et al., 2001; Dubois, 2005; Barnet, 2011; Cinelli et al., 2015), chemical analysis of bedrock and soils (Ielsch et al., 2010; Drolet et al., 2013), and airborne eU (equivalent uranium) measurements (Åkerblom, 1995; Ford et al., 2001; IAEA, 2003; Smethurst et al., 2008; Drolet et al., 2013). Many studies have investigated relationships between geology and indoor radon (e.g. Damkjaer and Korsbech, 1988, Gundersen, 1993; Sundal et al., 2004; Bossew et al., 2008; Appleton and Miles, 2010; Friedmann and Gröller, 2010; Garcia-Talavera et al., 2013), some of them aiming to characterise geology according to a radon potential derived from indoor radon measurements. Other studies have investigated the influence on indoor radon of geology together with construction-related variables (Hunter et al., 2009; Kemski et al., 2009; Hauri et al., 2012; Demoury et al., 2013). More recently data-driven approaches have been used to arrive at optimal groupings or characterisations of geological classes (Bossew, 2014, 2015; Kropat et al., 2015).

An earlier Norwegian study (Smethurst et al., 2008) used a combination of airborne eU, bedrock geology, drift geology, and indoor radon measurements to produce a radon risk map of the Oslofjord region. Although the study found an encouraging relationship between eU and indoor radon, it was limited in its geographical extent by the sparsity of eU and indoor radon data outside of the Oslo region, and it did not attempt any quantitative evaluation of its hazard classifications. A new study in the Oslo region, incorporating an enlarged indoor radon data set, and which compares the predictive power of eU and geology, is presented elsewhere in this issue (Smethurst et al., in this issue).

In Norway, although airborne geophysics coverage is anticipated to increase in the coming years, relatively little eU data are currently available outside of the Oslo region, and soil-gas radon measurements do not exist in significant quantities. Providing radon hazard estimates at a national level therefore relies on a good understanding of the relationship between geology and indoor radon concentrations.

The classifications of mapped geology, and the boundaries associated with them, suffer from a degree of subjectivity, and some inhomogeneity of radon properties within geological polygons can be anticipated (Miles and Appleton, 2005). Nevertheless, mapped digital geology can be expected to reflect much of the observed variation in surface radon levels, and its availability on a national level makes it the only feasible approach to generate radon hazard predictions for the whole of mainland Norway.

This study makes use of a new national dataset of indoor radon concentration measurements, together with digital bedrock and drift geology datasets, to study the relationships between geological classes and indoor radon, and to characterise geological classes in terms of radon potential. We use this radon potential to produce radon hazard predictions for the whole of mainland Norway, even in areas where few or no indoor radon measurements exist, and we evaluate the performance of two classification schemes as predictors of radon-prone areas.

2. Method

In this work we define *RP* (radon potential) for an area as the percentage of dwellings having annual average radon concentrations at or above a given threshold; we use RP_{200} to denote radon potential with a threshold of 200 Bq/m^3, and we define local areas as *radon affected* if RP_{200} is 20% or above, and as *less affected* otherwise. GIS-related analysis, map production, and classification work throughout this study have been performed using the QGIS (QGIS Development Team, 2015) software tool; additional statistical analysis has been performed using Analyse-it (Analyse-it Software Ltd, Leeds, UK) as well as our own custom software.

2.1. Datasets

Three datasets have been used in this study: 1) a national indoor radon database compiled and held by NRPA (NRPA, 2014); 2) a digital bedrock geology map at 1:250 000 scale from the Geological Survey of Norway (NGU) (NGU, 2015a); 3) NGU's digital drift geology map at mixed scales (1:50000 to 1:1000000) (NGU, 2015b).

2.1.1. Indoor radon

The indoor radon dataset (NRPA, 2014) consists of 34,563 georeferenced radon measurements from ground-floor living rooms and ground-floor bedrooms in dwellings throughout mainland Norway. Measurements were performed using alpha-track detectors over a minimum of 2-month periods during the winter months, and each measurement has been converted into an estimate of annual average radon concentration. The geographical distribution of indoor measurements, averaged over 10 km × 10 km cells, is illustrated in Fig. 1; the distribution of RP_{200} values calculated on 10 km × 10 km cells is shown in Fig. 2. Indoor radon concentrations are known to follow an approximately log-normal distribution (Bossew, 2010); statistical tests are therefore typically performed on the logarithm of the radon concentrations, and geometrical means are a more appropriate measure of average indoor radon concentration. The distribution of the natural logarithm of indoor radon concentrations is shown in Fig. 3.

2.1.2. Bedrock geology

The bedrock dataset consists of 31,632 polygons covering the whole of mainland Norway, each classified into one of the 38 bedrock categories shown in Table 1. Among the more prevalent categories are *Gabbro or amphibolite* (n = 3382) and *Dioritic to granitic gneiss* (n = 3234).

NGU's 1:250 000 bedrock dataset does not contain an *alum shale* category; due to the known association of alum shale with elevated indoor radon levels, any geological polygons including alum shale were reclassified into a new BEDID = 100 *(Alum shale)* category (Table 1).

All the bedrock categories covering mainland Norway contained at least one indoor radon measurement.

2.1.3. Drift geology

The drift geology dataset consists of 616,761 polygons, each classified into one of 49 drift geology categories. Table 2 shows the 32 drift categories whose polygons contain at least one indoor radon measurement. Table 2 excludes a further 17 categories

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