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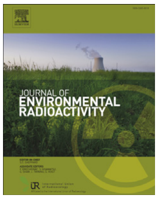

The predictive power of airborne gamma ray survey data on the locations of domestic radon hazards in Norway: A strong case for utilizing airborne data in large-scale radon potential mapping

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ABSTRACT

It is estimated that exposure to radon in Norwegian dwellings is responsible for as many as 300 deaths a year due to lung cancer. To address this, the authorities in Norway have developed a national action plan that has the aim of reducing exposure to radon in Norway (Norwegian Ministries, 2010). The plan includes further investigation of the relationship between radon hazard and geological conditions, and development of map-based tools for assessing the large spatial variation in radon hazard levels across Norway. The main focus of the present contribution is to describe how we generate map predictions of radon potential (*RP*), a measure of radon hazard, from available airborne gamma ray spectrometry (AGRS) surveys in Norway, and what impact these map predictions can be expected to have on radon protection work including land-use planning and targeted surveying.

We have compiled 11 contiguous AGRS surveys centred on the most populated part of Norway around Oslo to produce an equivalent uranium map measuring 180 km × 102 km that represents the relative concentrations of radon in the near surface of the ground with a spatial resolution in the 100 s of metres. We find that this map of radon in the ground offers a far more detailed and reliable picture of the distribution of radon in the sub-surface than can be deduced from the available digital geology maps.

We tested the performances of digital geology and AGRS data as predictors of *RP*. We find that digital geology explains approximately 40% of the observed variance in *ln RP* nationally, while the AGRS data in the Oslo area split into 14 bands explains approximately 70% of the variance in the same parameter. We also notice that there are too few indoor data to characterise all geological settings in Norway which leaves areas in the geology-based *RP* map in the Oslo area, and elsewhere, unclassified. The AGRS *RP* map is derived from fewer classes, all characterised by more than 30 indoor measurements, and the corresponding *RP* map of the Oslo area has no unclassified parts. We used statistics of proportions to add 95% confidence limits to estimates of *RP* on our predictive maps, offering public health strategists an objective measure of uncertainty in the model. The geological and AGRS *RP* maps were further compared in terms of their performances in correctly classifying local areas known to be *radon affected* and *less affected*. Both maps were accurate in their predictions; however the AGRS map out-performed the geology map in its ability to offer confident predictions of *RP* for all of the local areas tested.

We compared the AGRS *RP* map with the 2015 distribution of population in the Oslo area to determine the likely impact of radon contamination on the population. 11.4% of the population currently reside in the area classified as *radon affected*. 34% of ground floor living spaces in this affected area are expected to exceed the maximum limit of 200 Bq/m^3, while 8.4% of similar spaces outside the affected area exceed this same limit, indicating that the map is very efficient at separating areas with quite different radon contamination profiles.

The usefulness of the AGRS *RP* map in guiding new indoor radon surveys in the Oslo area was also examined. It is shown that indoor measuring programmes targeted on elevated *RP* areas could be as much as 6 times more efficient at identifying ground floor living spaces above the radon action level

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compared with surveys based on a random sampling strategy. Also, targeted measuring using the AGRS *RP* map as a guide makes it practical to search for the worst affected homes in the Oslo area: 10% of the incidences of very high radon contamination in ground floor living spaces (≥800 Bq/m^3) are concentrated in just 1.2% of the populated part of the area.

1. Introduction

Radon is a naturally occurring radioactive gas generated in the ground beneath and around dwellings (Stranden, 1986; HPA, 2009). Radon gas is the most significant natural source of human exposure to ionising radiation and most of that exposure occurs in the home (UNSCEAR, 2008; WHO, 2009). There is now overwhelming evidence supporting the view that prolonged exposure to radon in the home is responsible for many new cases of lung cancer each year (Lubin et al., 2004; Darby et al., 2005, 2006; Krewski et al., 2005, 2006). In an effort to reduce exposure to radon in Norwegian buildings (Norwegian Ministries, 2010), a radon *action limit* of 100 Bq/m^3 has been defined for new buildings, above which radon reducing mitigation measures should be implemented. A further *maximum limit* has been set at 200 Bq/m^3 above which all effort should be made to reduce radon concentrations. In existing dwellings, these limits are recommendations and not mandatory.

The amount of radon available to enter dwellings depends on local geological conditions (Tanner, 1964; Nero and Nazaroff, 1984; Stranden et al., 1985; Peake, 1988; Nazaroff, 1992; Hutri and Mäkeläinen, 1993; Albarracin et al., 2002; Sundal et al., 2004a, 2004b), while entry into the buildings depends on their physical characteristics, their styles of use, and meteorological conditions (Hubbard et al., 1988; Nazaroff, 1988; Robinson and Sextro, 1997; Miles, 2001; Font and Baixeras, 2003; Janssen, 2003; Froňka, 2011; Diallo et al., 2015). Despite complex variability in ground conditions and dwelling properties from one place to another in Norway, there is clear evidence for a correlation between the amount of radon generated in the ground around dwellings and the amount of radon that ends up inside the dwellings to present a risk to human health (Smethurst et al., 2008a). In radon mitigation, it is logical to identify affected dwellings and communities through direct means – measuring radon levels in occupied spaces inside buildings (Miles, 2001; Dubois, 2005; WHO, 2009). In 2014 the Norwegian Radiation Protection Authority (NRPA) held 120,880 long-term alpha track measurements of radon concentrations made in Norwegian dwellings (Strand et al., 1991, 1992, 2001, 2003; NRPA, 2014). Where indoor measurements are few or irregularly distributed, and where no dwellings currently exist, it is necessary to use information on radon concentrations in the ground to identify areas that might currently be radon prone or could become radon prone should those areas be developed for human habitation in the future (e.g. Stranden and Strand, 1988; Sundal et al., 2004b). Radon in the ground can be detected directly through soil gas measurement programmes (Pinault and Baubron, 1996; Neznal et al., 1996, 1997; Winkler et al., 2001; Papastefanou, 2002; Dubois, 2005; Cinelli et al., 2015) and though airborne gamma-ray spectrometer surveying (AGRS; Galbraith and Saunders, 1983; Minty, 1997; Minty et al., 1997; IAEA, 2003), or indirectly through geochemical investigation (e.g. Bossew et al., 2013), or simply through the identification and delineation of geological settings typically associated with elevated radon emanation and radon transport (NGU, 2011; Sundal et al., 2004b). Direct methods with sufficient spatial detail should outperform indirect methods, but often the choice of method to use is strongly influenced by the availability of data, and the costs and delays associated with acquiring new data.

The spatial coverage offered by indoor data is currently insufficient to generate useful radon potential maps for many communities across Norway. Therefore, the NRPA and Geological Survey of Norway (NGU) are pooling data resources to generate supporting *RP* maps constrained by indicators of radon in the outdoor environment. Soil gas measurements are not available in useful number in Norway, while 11 contiguous high spatial resolution AGRS surveys are available for the most densely populated part of Norway around Oslo (Fig. 1, Table 1, and Fig. 2). Those AGRS surveys can be merged and usefully provide a high resolution geogenic radon map for that heavily populated area – southeast Norway – expressed in terms of equivalent concentrations of the parent nuclide uranium-238 (eU; Fig. 3). When the eU map is compared with indoor radon data from the same area (Fig. 4), it can reliably be transformed into an *RP* map covering the entire survey area – where indoor radon data are available, and also where they are not. The main focus of the present contribution is to describe how we now generate predictions of *RP* from the AGRS data and what impact these predictions can be expected to have on radon protection work. Smethurst et al. (2008a) were the first to use AGRS data to predict levels of radon hazard across the Oslo area. That work is now worth updating because the area covered by survey data is considerably larger now (Fig. 1), and we have access to twice the

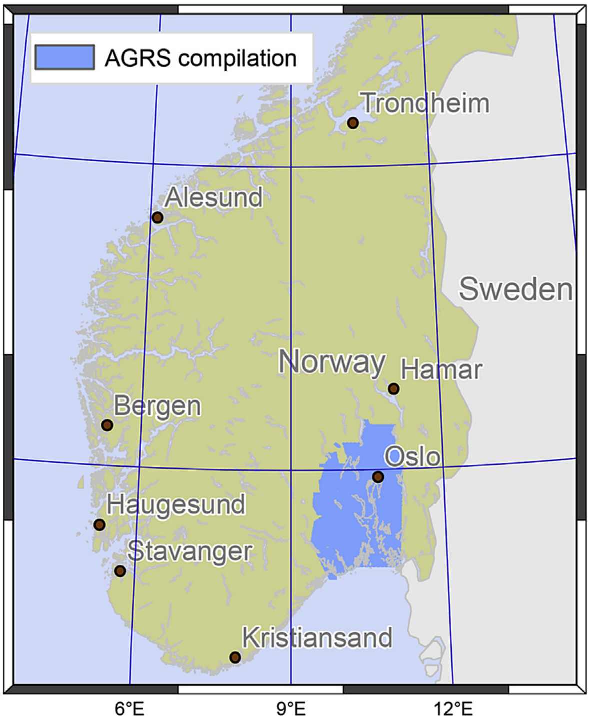

Fig. 1. Southern Norway and the extent of the airborne gamma ray survey compilation centred on Oslo (blue).

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