Nat. Hazards Earth Syst. Sci., 14, 739–749, 2014
www.nat-hazards-earth-syst-sci.net/14/739/2014/
doi:10.5194/nhess-14-739-2014

Natural Hazards and Earth System Sciences
Open Access

Using geographic information systems for radon exposure assessment in dwellings in the Oslo region, Norway

R. Kollerud[1,5], K. Blaasaas[2], G. Ganerød[3], H. K. Daviknes[4], E. Aune[4], and B. Claussen[5]

[1]Agency for Health, City of Oslo, Storgata 40, 0182, Oslo, Norway
[2]Finance Norway, P.O. Box 2473 Solli, 0202, Oslo Norway
[3]Geological Survey of Norway, 7491 Trondheim, Norway
[4]Agency for Urban Environment, City of Oslo, P.O. Box 9336 Grønland, 0135, Oslo, Norway
[5]Institute of Health and Society, University of Oslo, P.O. Box 1130 Blindervn, 0318 Oslo, Norway

Correspondence to: R. Kollerud (ruby.kollerud@hotmail.com)

Received: 28 May 2013 – Published in Nat. Hazards Earth Syst. Sci. Discuss.: 28 June 2013
Revised: 24 January 2014 – Accepted: 23 February 2014 – Published: 3 April 2014

Abstract. Radon exposures were assigned to each residential address in the Oslo region using a geographic information system (GIS) that included indoor radon measurements. The results will be used in an epidemiologic study regarding leukemia and brain cancer. The model is based on 6 % of measured residential buildings. High density of indoor radon measurements allowed us to develop a buffer model where indoor radon measurements found around each dwelling were used to assign a radon value for homes lacking radon measurement.

Intraclass correlation coefficients (ICCs) were used to study the agreement between radon values from the buffer method, from indoor radon values of measured houses, and from a regression model constructed with radiometric data (e_{Th}, e_{U}) and bedrock geology. We obtained good agreement for both comparisons with ICC values between 0.54 and 0.68.

GIS offers a useful variety of tools to study the indoor-radon exposure assessment. By using the buffer method it is more likely that geological conditions are similar within the buffer and this may take more into account the variation of radon over short distances. It is also probable that short-distance-scale correlation patterns express similarities in building styles and living habits. Although the method has certain limitations, we regard it as acceptable for use in epidemiological studies.

1 Introduction

Norway has some of the highest concentrations in the world of indoor radon in dwellings , with an average radon concentration of 88 Bq m^{-3} and 27 % of the population exposed to levels higher than 100 Bq m^{-3} (Stranden et al., 1986; Strand et al., 2001; Stigum et al., 2003). On a national basis, the bulk of high radon values are in the areas around the capital Oslo. This includes both average concentrations and proportion of homes with elevated concentrations. In accordance with national and international recommendations, remedial measures in the homes are recommended if the annual mean radon concentration in living rooms exceeds 100 Bq m^{-3}. Norwegian authorities have set 200 Bq m^{-3} as maximum limit in newly built homes (WHO radon handbook, 2009; Norwegian Radiation Protection Authority NRPA, 2009).

Humans are exposed to many different sources of ionizing radiation, both natural and anthropogenic. Natural background radiation emerges from three sources: cosmic radiation, terrestrial radiation and internal radiation (UNSCEAR, 2000). Terrestrial radiation is originated from the radioactive materials potassium (K), uranium (U) and thorium (Th) that occur naturally in the ground; bedrock and sediments and their decay products with amongst others radon (^{222}Rn) from ^{238}U. By far, the most significant source of anthropogenic radiation exposure to the public is from medical procedures such as diagnostic X-rays, nuclear medicine, and radiation therapy.

^{222}Rn is the main source of background radiation exposing humans. This is a naturally occurring radioactive gas resulting from the decay of ^{238}U, which is the most common naturally occurring uranium isotope. Uranium is found in small quantities in all sediments and rocks, but the concentration varies. ^{222}Rn has a half-life of 3.82 days, and provides about 50 % of the total radiation dose for an average person (Appleton, 2007). The other radon isotopes have a shorter half-life than ^{222}Rn and are therefore not regarded as a considerable health issue. (IAEA, 2012).

Smethurst et al. (2006, 2008) compiled the airborne radiometric data for the Oslo area, strengthening the correlation of geology contributing to radon hazard. The same data set of airborne radiometric is used in this study, but here we are able to correlate the airborne radiometric data to more numerous georeferenced indoor radon measurements than in the study by Smethurst et al. (2006, 2008).

Airborne radiometric data (e_{Th}, e_{U} and K; Smethurst et al., 2006) have been used for improving the accuracy of maps of indoor radon. Appleton et al. (2008) found good agreement between radon maps modeled from airborne radiometric data on both e_{U}, e_{Th} and K and soil geochemical data compared with radon maps produced by conventional mapping, based solely on geochemical and indoor radon data. UK maps modeled with airborne data on e_{U}, e_{Th} and K identified some additional areas where radon risk appears to be relatively high compared to conventional radon maps. Scheib et al. (2006) reported K as a good indicator of the clay content and permeability of bedrock.

In a study by Tzortzis and Tsertos (2004) the content of the radioactive elements Th, U and K found in soils reflect the bedrock source. In terms of natural radioactivity, igneous rocks of granitic composition may be strongly enriched in Th and U (on an average $15\,\mu g\,g^{-1}$ of Th and $5\,\mu g\,g^{-1}$ of U), compared to rocks of basaltic or ultramafic composition ($< 1\,\mu g\,g^{-1}$ of U; Faure, 1986; Ménager et al., 1993). For that reason, higher radiation levels are associated with granitic rocks.

Permeability in the ground is also an important factor in the occurrence of radon. Areas of high permeability are therefore more likely to be exposed to radon (Sundal et al., 2004), while areas with low permeability, such as clay, may have lower radon exposure (Smethurst et al., 2008).

In Norway factors such as geology, ventilation systems, ventilation habits and floor properties are found to have the strongest correlation with indoor radon levels. Building materials are less important, probably because of a large percentage of the houses in Norway are built of wood (Sundal et al., 2004), however differences can be observed for instance between coniferous and deciduous woods.

The understanding of radon sources and radon transport mechanisms has evolved over several decades. In the 1950s, high concentrations of radon were observed in public and private water. Initially, concern about radon in water focused on health effects from ingesting the water. Later, it was determined that the primary health risk of radon in water was from the inhalation of radon released indoors. By the mid-1970s, emission of radon from building materials was found to be a problem in some areas due to the use of alum shale with enhanced levels of uranium. By 1978, houses were identified where the indoor radon concentrations were not associated with well-water transport or emission from building materials. Soil-gas infiltration became recognized as the most important source of indoor radon. Other sources, including building materials and well water, are of less importance in most circumstances (WHO radon handbook, 2009).

Radon is a well-established human lung carcinogen (Hussain et al., 1997; Weaver et al., 1997; International Agency for Research on Cancer (IARC)). The IARC considered that there is sufficient evidence to classify radon and its decay products as carcinogenic to humans (IARC, 2001; WHO handbook, 2009). A growing number of studies are attempting to clarify the relationship between exposure to radon in homes and the risk of cancer in children (Tong et al., 2012). Several ecological studies are based on surveys of radon on the basis only of municipal boundaries and postal codes (Richardson et al., 1995; Thorne et al., 1996; Evrard et al., 2005). Other studies have developed predictive models of radon exposure (Kohli et al., 2000; Raasschou-Nielsen et al., 2008; Kendall et al., 2012).

Several authors point out geology as a useful, but insufficient indicator for estimating radon in buildings (Gundersen and Schumann, 1996; Hulka et al., 1997; Miles, 1998b). Therefore, measurements inside buildings are necessary for estimating indoor radon concentrations. Maps of radon risk have a degree of uncertainty when classifying radon in a house. There are many sources of uncertainty and bias in the data. Miles and Appleton (2005) summarize some of these uncertainties. In areas with few measurements, clusters of high radon measurements can influence the map of a relatively large area. Radon measurements used in the survey can be from willing participants who possibly may have higher radon levels than reluctant participants. There may be considerable uncertainty in the estimates of annual average radon concentrations in dwellings, especially at lower radon levels; and there may be uncertainty in the coordinates of both the dwelling and geological boundaries.

The purpose of this work was to develop a method for assigning radon concentration values to unmeasured dwellings in the Oslo region, Norway, which will be further used in an epidemiological study of leukemia and brain cancer.

2 Materials and methods

2.1 The study area

The Oslo region is an area of approximately 10 000 km^2. Almost 2 million people live there, representing around 40 % of the entire Norwegian population. A total of 1 056 794 dwellings were included from the counties of Oslo, Akershus, Vestfold and Østfold, and the municipalities of Gran, Jevnaker, Lunner, Lillehammer, Gjøvik, Vestre toten, Østre toten, Søndre land, Ringerike, Hole, Lier, Nedre Eiker, Røyken, Drammen and Hurum.

In Norway an area is registered as densely populated if at least 200 people are living there and the distance between houses normally not exceed 50 m.

The Norwegian Mapping Authority has, through a geographical information system (GIS), access to coordinates of every Norwegian residence linked to its address. The coordinates are obtained from maps at scale of 1 : 5 000. The accuracy of the coordinates used in this study is within 5 m of the building center point. To estimate radon exposure in dwellings the GIS program ArcGIS 9.2 (ESRI) was used.

The project was approved by the Norwegian Data Protection Authority and the Regional Committees for Medical and Health Research Ethics (REC).

2.2 Data

Indoor radon measurements have been collected by the Norwegian Radiation Protection Authority (NRPA) as a result of several radon measurement campaigns in the Oslo region during the period 1998–2010 (Fig. 1). The programs were largely based on measurements of indoor radon concentrations in dwellings selected at random from the housing stock (Smethurst and Strand, 2008). The measurements were performed according to the recommendations from the NRPA (NRPA, 2008) and the Working Group of the effort against radon in Norway (WGR).

Radon concentrations in a home can vary over seasons. WGR recommends that measurements to assess health risks are carried by film tracks for at least 2 months during the period from October to April (WGR, 2007–2009). In this study 97.5 % of the radon measurements were carried out between October and April; 82.6 % were carried out during 2 months or more. A total of 41 515 indoor radon measurements in the Oslo region were obtained from the NRPA radon database. For homes with multiple measurements in several rooms the average was used.

Approximately 2.5 % ($n = 1071$) of the radon measurements were lacking address information or lacking radon values and were excluded. The coordinates of the dwellings were obtained from a public registry of cadastral properties, addresses and buildings in Norway (GAB).

2.2.1 Type of dwelling and radon measurements

NRPA recommends anyone living in one of the three lowest floors above ground to measure the radon concentration. In the study area (except Oslo) 98.2 % of the dwellings are low-level houses (SSB, 2013). The equivalent percent for Oslo is 84.3 %. The most common type of measured dwelling was detached houses, representing 74.5 % of all radon measurements (Table 1).

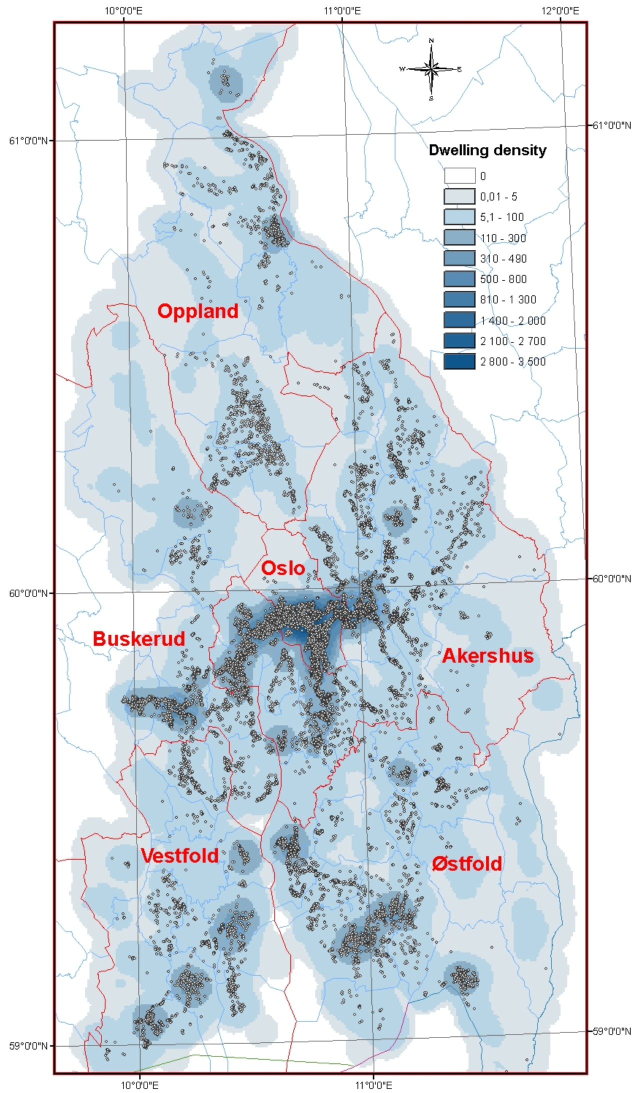

Fig. 1. Indoor radon measurements in the Oslo region by dwelling density. The gray points represent indoor radon measurements. The color blue in the map represents density of dwellings; darker blue represents areas with the highest dwelling density.

Table 1 shows that 87.1 % of the radon measurements used in this study was from low-level houses and 2.7 % was from the first three floors of apartment buildings. Of the radon measurements 84 % were made in the bedroom and main living room and other living areas; 15 % were missing information on type of room. These were however included because they were made in the first and second floors of the dwelling; and 1 % coming from nonliving-room areas were excluded.

Of the radon measurements 91.6 % had information on floor level, and 99.9 % of these were below the third floor. Only 14 radon measurements were made on the third floor and 67 radon measurements were made above the third floor;

Table 1. Dwelling style in the Oslo region and number of radon measurements (from Statistics Norway, 2013).

Dwelling style	Municipalities outside Oslo	Oslo	Radon measurements	
	%	%	Number	%
Detached	76.3	35.6	30 133	74.5
Semi-detached	11.0	19.9	3149	7.8
Row houses	10.9	28.8	1931	4.8
Apartment building	1.6	15.5	1117	2.7
Other styles	0.2	0.2	464	1.2
Missing information			3650	9.0
Total	100	100	40 444	100

where 61 of these 67 radon measurements were from ground-contact apartments. The radon concentration in ground-contact apartments are similar to those in low-rise residential building located in the same area (Valmari et al., 2012). The 8.4 % lacking information on floor level were included because they were made in low-level houses. Of the radon measurements 66.7 % are missing information on floor level were from Oslo. In 2008/2009 a radon survey was performed in Oslo (Health and Welfare, 2008/2009). An invitation letter was sent to 40 000 homeowners living on the first three floors inviting them to measure radon in the rooms where they spend most of their time. More than 5100 homeowners participated in this campaign.

The annual average radon concentration for each dwelling was used in this study. Distribution of radon levels in the dwellings approximated a log-normal distribution. We analyzed radon values for all municipalities outside of Oslo for different dwelling types including underground, first and second floors. For Oslo the annual average concentration for each dwelling was already calculated by averaging the results of the radon measurements.

Since the 1970s it has been popular in Norway to share dwellings; i.e., single family houses with a basement apartment with independent entrance. Around 10 % of singles and single parents in Norway live in basement flats (Lappegår and Nordvik, 1998). Lappegår and Nordvik (1998) calculated that around 6.5 % of all houses in Norway are basement apartments. Of the total radon measurements 25.5 % were done in basements; 70.4 % of these were made in main living areas, bedrooms and others places where people spend most of their time. Of the measurements 0.8 % were made in nonliving areas, and 28.4 % lacked information on type of room. The mean radon value of measurements lacking room-type information was 181.6 Bq m^{-3}. Since the mean value of radon from main living room areas were 186.2 Bq m^{-3} the results were pooled.

Information on the type of house for each dwelling unit in the Oslo region was not complete, but information on how many dwelling units were found in each coordinate point was given. The coordinates for an address describe the geographic point the address refers to, and will normally specify the access to a building or dwelling.

Table 2 presents a description of mean radon values according to number of dwelling units in each coordinate. We categorized the data as follows: if it was one dwelling unit in a coordinate point it was categorized as a detached house, if it was two dwellings it was categorized as a semi-detached house. It is possible that some of these dwelling units with two housing units were detached houses with a basement apartment. Coordinate points with three to four dwelling units were categorized as low-level buildings, and if it was five or more dwelling units in a coordinate point it was categorized as an apartment building.

2.2.2 Airborne gamma spectrometry and geological data

Mapping ^{40}K, ^{232}Th and ^{238}U in the Oslo region has been carried out by Geological Survey of Norway (NGU) through airborne surveys in the period 1981–2003. Gamma spectrometry detects uranium-bearing material in the earth's surface. Measurements detect gamma rays down to about 40 cm depth. Based on the measurements NGU has prepared maps of e_{Th}, e_{U} and K (Fig. 2). A more detailed description of these studies is documented in Smethurst et al. (2006, 2008). The concentrations of Ra in some common Nordic rocks can be very high. A granitic rock containing uranium might have concentrations of ^{226}Ra between 100 and 600 Bq kg^{-1}. Alum shale from the middle Cambrian period may have concentrations of ^{226}Ra ranging from 120 to 600 Bq kg^{-1} and alum shale from the upper Cambrian/lower Ordovician may have ^{226}Ra concentrations from 600 to 5000 Bq kg^{-1} (NRPA, 2012).

The NGU and the NRPA have produced maps of radon hazards in the Oslo region (Smerthurst et al. 2008) presenting radon awareness of high or moderate level.

For the radon awareness maps bedrock geology was coded into four categories according to the uranium content in the different rock types: low (gneiss, mafic intrusives and sediments), moderate (monzonite, latite, syenite and trachytes), high (granite and rhyolite) and very high (alum shale). A more detailed description can be found in Smerthurst et al. (2006, 2008).

The permeability of the superficial deposits (Quaternary Period) varies from impermeable clay to coarse gravel with high permeability. The masses are classified as described in Table 4.

Data on airborne gamma ray spectrometry measurements, bedrock geology and drift geology used in this study is obtained from the work described above.

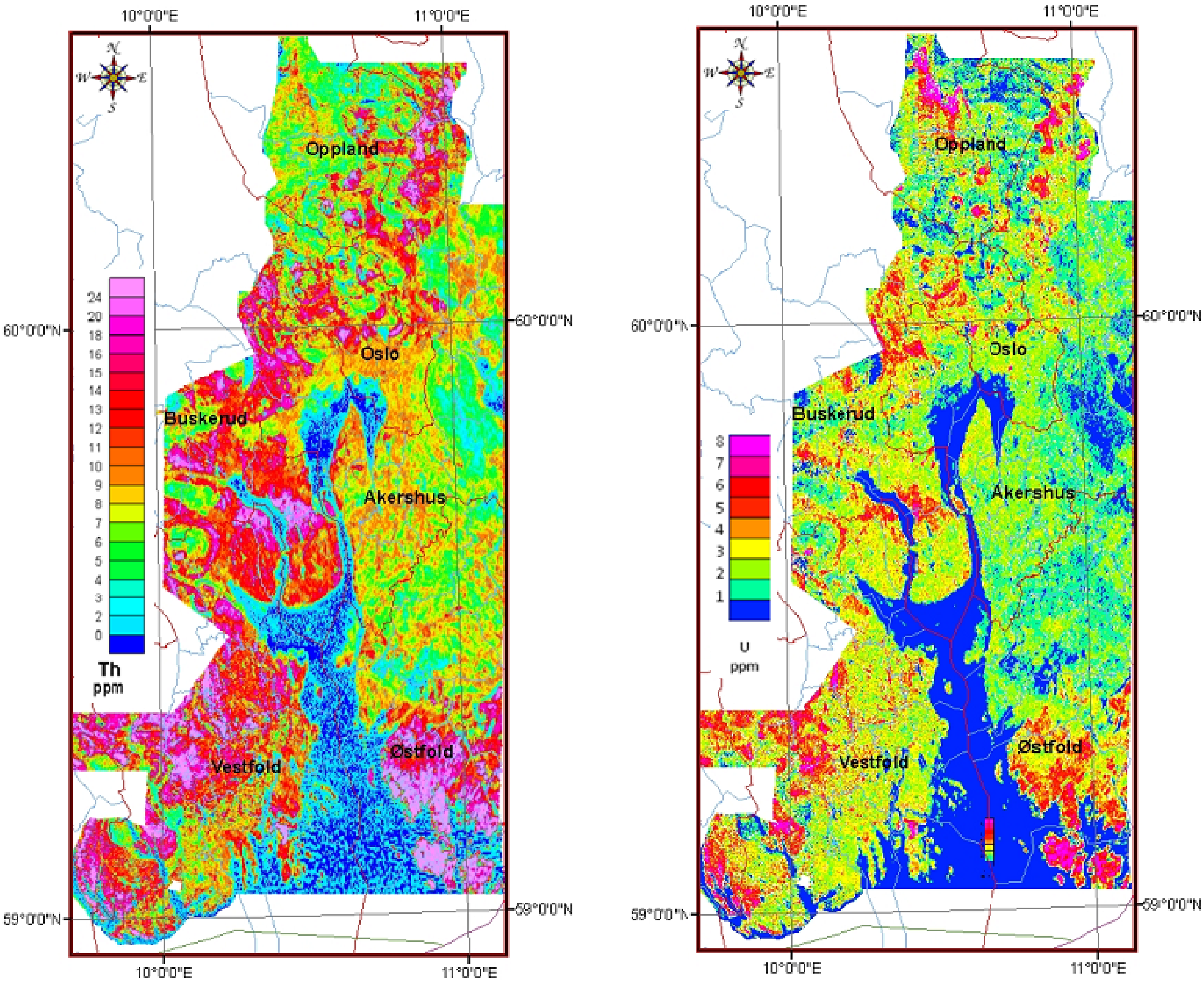

Fig. 2. Thorium and uranium concentrations based on gamma ray spectrometer surveys for the Oslo region by airborne gamma-ray spectrometry. Surveys were carried out from 1981 to 2003 by the Geological Survey of Norway (Smethurst et al., 2006, 2008).

2.3 Prediction of indoor radon concentrations in dwellings

To assign a radon value to each dwelling GIS was used to digitize and integrate the information. Data included were indoor radon measurements, ground permeability, bedrock geology and data on natural radioactivity in the ground based on airborne gamma-ray spectrometry. A graphic explanation is given in Fig. 3.

To estimate the radon levels of dwellings without measurements, the following steps were used.

1. All dwellings sharing the same coordinate point as a dwelling with at least one measurement inherited the same radon value or the mean radon value if with more than one measurement. If several dwellings shared the same coordinate point the dwelling with the highest mean value in each coordinate point was used to construct buffers.

2. Around each remaining dwelling a buffer with a 300 m radius was constructed. If the buffer included five or more measured dwellings, the unmeasured dwelling was given the same radon value as the arithmetic (AM) and geometric mean (GM) calculated from measured dwellings inside the buffer.

3. If less than five measurements were encountered inside the buffer the radius was increased to 500, 1000 or 2000 m until the buffer included at least five measured dwellings.

4. Dwellings with less than five radon measurements within a radius of 2000 meters were given the AM and

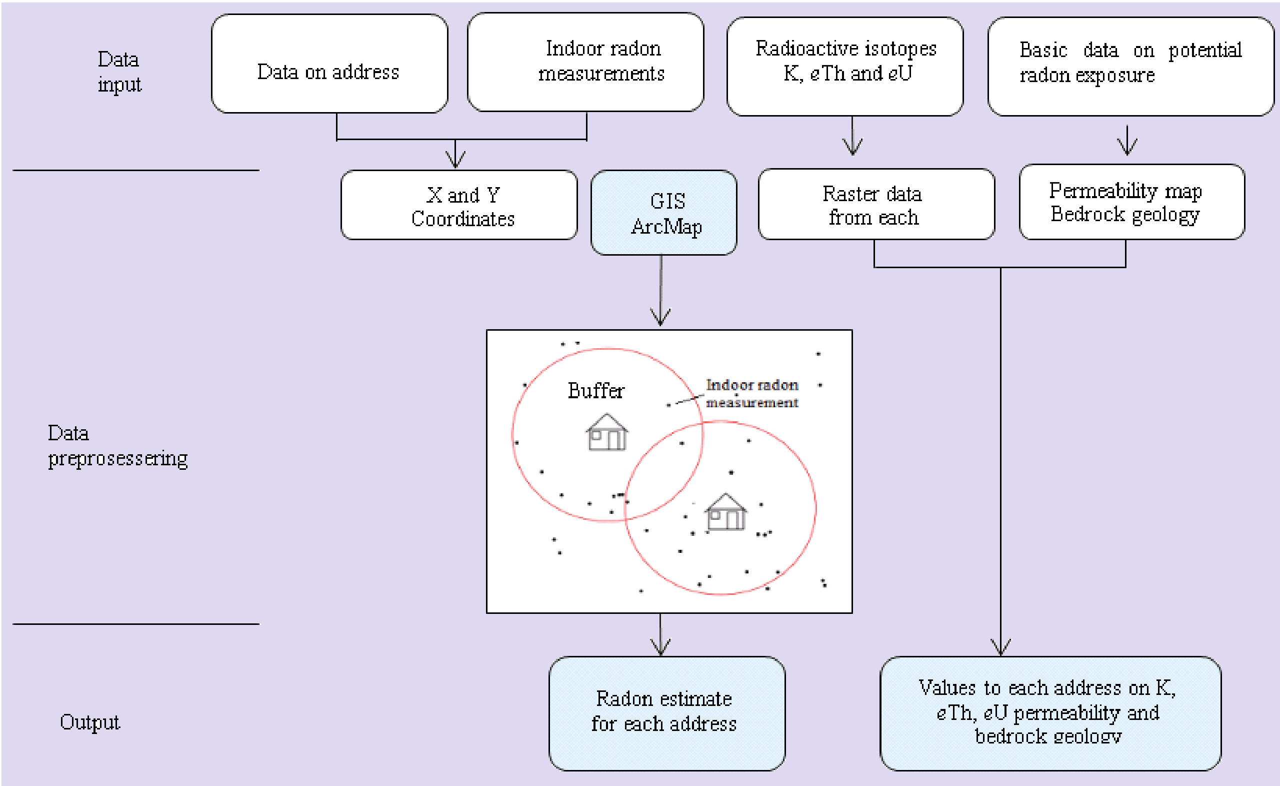

Fig. 3. Flow chart illustrating the data analysis and integration methodology. The house in the center represents a dwelling without a radon value and the red circle is the associated buffer.

GM of the indoor radon measurements found in the buffer circle.

5. Dwellings with no radon measurements within a radius of 2000 m were given the same radon value as the closest measured dwelling.

In addition to radon values from the buffer each house got a category of radon risk: low, medium or high based on bedrock geology, uranium concentration and permeability found at each coordinate point.

2.4 Statistical methods

Pearson's correlation coefficient was used to study the relationship between measured indoor radon concentrations, airborne radiometric measurements, bedrock geology and ground permeability. To study this relationship, buffers were constructed around each house with indoor radon measurements ($n = 28\,396$) after the same procedure as described in Sect. 2.3.1. Of the dwellings 26 310 had complete information on bedrock geology and ground permeability. Of these, 22 155 dwellings had complete information of isotopes K, e_{Th} and e_{U}. In each buffer the GM and AM was calculated for each of the isotopes ^{40}K, ^{232}Th and ^{238}U. Additionally, the percentage of radon measurements above 200 Bq m^{-3} in each buffer was estimated based on the procedure described in Sect. 2.3.1. Buffers with 20 or more radon measurements were used for the analysis. A total of 6901 buffers had 20 or more measurements.

These 22 155 buffers were also the basis for constructing a regression model. Independent variables were airborne radiometric measurements of K, e_{Th}, and e_{U} (Fig. 2), bedrock geology (Table 3) and ground permeability (Table 4). The dependent variable was the natural logarithm of the indoor radon concentration. We performed a stepwise regression model starting with all variables. Variables not significant at the 5 % level were removed from the model.

Table 2. Radon average by the number of dwelling units found at each coordinate point.

Number of dwelling units at each coordinate point	Number	Radon mean	Std. Error	95 % confidence interval
1 dwelling unit	22 215	155.2	2.0	151–159
2 dwelling units	2233	153.8	6.9	140–167
3 and 4 dwelling units	457	151.8	12.3	127–176
5 or more dwelling units	634	84.97	5.4	74–95
Missing information	2857			
Total	28 396			

Table 3. Annual average indoor radon concentrations over 200 Bq m^{-3} in homes standing on different rock types.

Rock type	% ≥ 200 Bq m^{-3}	Number of observations
Alum shale	46 %	645
Granite/rhyolite	25 %	1169
Monzonite/latite	13 %	553
Syenite/trachyte	16 %	168
Sediments	11 %	260
Mafic intrusives	19 %	2029
Gneiss	8 %	3912

Total number of observations: 8736
From Smethurst et al. (2008)

Table 4. Annual average indoor radon concentrations over 200 Bq m^{-3} in homes surrounded by different superficial deposits.

Drift geology	% ≥ 200 Bq m^{-2}	Number of observations
Moderate permeability	20 %	4318
High permeability	12 %	927
Low permeability	8 %	1440
Bedrock/thin cover	12 %	1316
Anthropogenic fill	6 %	939

Total number of observations: 8940
From Smethurst et al. (2008)

Further analyses were conducted with three different sets of data. The first data set was of results of measurements in homes, including GM and AM of indoor radon measurements, the percentage of radon measurements above 200 Bq m^{-3}, and the GM and AM of K, e_{Th}, and e_{U} were compared through the Pearson correlation coefficient. The second data set was the radon estimate based on the regression model. The third data set included the originally measured dwellings, but this time with radon estimates based on the buffer method as described in Sect. 2.3.1.

Intraclass correlation coefficients (ICCs) were used to study the agreement between radon values estimated from the buffer method and the indoor radon measurements. ICC was also used to study the agreement between estimates of radon from the buffer method and radon estimates from the regression model. The ICC is generally used to assess agreement between two continuous variables and can be interpreted as a measure of reproducibility or reliability (Fleiss, 1986). Here, ICC was used to see how well it classifies the house according to its radon value, the reliability of the method or the reproducibility of the results. We used the ICC's two-way, mixed-effects model for calculating the ICC values. SPSS software version 20 was used in all analyses.

3 Results

Radon values were estimated for 1 055 495 dwellings (468 350 residential buildings) in the Oslo region. A total of 83.8 % of the dwellings were located in urban areas.

Dwellings sharing the same entrance coordinate were given the same radon value or average of all measured radon values at this point. A total value of 40 474 (3.8 %) dwellings got radon estimates in this way. Based on buffers, 1 008 804 dwellings or 95.6 % of the material were given radon estimates. In 4.4 % of the material we could not find any measured dwelling inside a buffer of 2000 m radius. The dwelling was given the same radon value as the nearest house.

Of the buffers 53.7 % had a radius of 300 m, 17.9 % had 500 m, 15.5 % had 1000 m and 13 % had a radius of 2000 m. Of the dwellings 94.2 % had five or more radon measurements inside the buffer. Among the buffers 2.1 % had 3 or 4 radon measurements.

If we look at the maximum value of radon found at each coordinate point, we find that 42.2 % of the dwellings had a value above 100 Bq m^{-3}, 23.4 % of dwellings had a radon value between 100 and 200 Bq m^{-3}, and 19.8 % of the dwellings were above 200 Bq m^{-3}. Analyses of the average value of radon in each coordinate show that 36.8 % of the homes was above 100 Bq m^{-3}, 21.6 % between 100 and 200 Bq m^{-3} and 15.2 % were above 200 Bq m^{-3}, the recommended maximum value of indoor radon concentration (NRPA, StrålevernInfo 25.09).

Geological data and airborne gamma ray spectrometry measurement results were available for 70 % of the dwellings.

3.1 Relationship between indoor radon measurements and airborne gamma ray spectrometry measurements

From each buffer with original radon measurements ($n =$ 22 155) we obtained values for both AM and GM. The best correlation was observed between GM of indoor radon measurements and AM of K, e_{Th} and e_{U}. GM of indoor radon measurements, unlike the AM, tends to mitigate the effects of very high or very low values. GM is also most commonly used for characterizing indoor radon concentrations. Regarding K, e_{Th} and e_{U} we used AM because these data were closer to normal distribution.

Pearson's correlation coefficient between GM of indoor radon measurements found within the buffers containing 20 or more measurements ($n = 9405$) and AM for e_{U} in areas with alum shale showed a correlation of 0.74. The correlation increased to 0.87 when buffers with 30 or more radon measurements were analyzed. The correlation between the percentage of radon measurements above 200 Bq m^{-3} and AM of e_{U} in buffers with 30 or more radon measurements was 0.72.

Pearson's correlation coefficient between GM of indoor radon measurements found within the buffers containing 20 or more measurements and AM of K, e_{Th}, e_{U} was 0.42, 0.67 and 0.65, respectively. This correlation increased to 0.48, 0.73 and 0.69 for K, e_{Th} and e_{U}, respectively, for buffers with 30 or more radon measurements.

Linear regression models were derived from the indoor radon measurements, radiometric data (e_{Th}, K and e_{U}) and bedrock geology. Stepwise regression indicated that K and e_{Th} were less significantly associated than e_{U}. e_{Th} accounted for only 0.3 % of the total variance, but was included in the model. The percentage of variance explained by e_{U} and bedrock geology was higher with 16 and 15 % respectively. Permeability is documented as an important predictor for radon (Sundal et al., 2004), but in our analysis it was not significant. A possible explanation might be the fact that a large number of houses lacked permeability data.

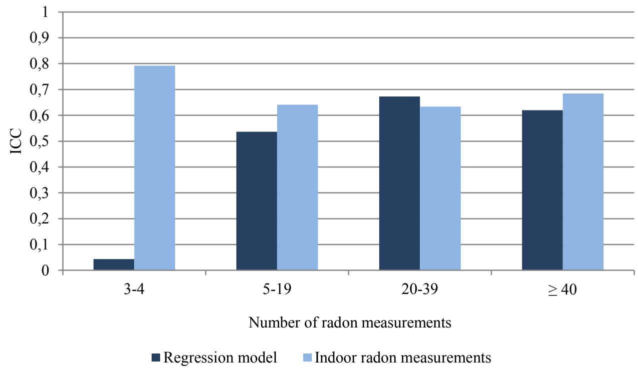

Fig. 4. Comparison of ICC values between estimates of radon from the buffer method, regression model and indoor radon measurements, distributed by the number of radon measurements in the buffers.

3.2 Reliability of the results

The value of a reliability estimate tells us the proportion of variability in the measure attributable to the true score. For quantitative measurements, ICC is the principal measurement of reliability (Shrout and Fleiss, 1979). An ICC value of 1.00 represents perfect agreement while 0.00 means no consistency. In our study a house could have three radon values from three different methods. One radon value from the buffer method, one value from the regression model and one value from measurements made directly in the dwellings. These three measurements were compared to analyze the degree of agreement between them, which means how much the radon value from the buffer method agrees with the other two methods.

Analysis of buffers with five or more indoor radon measurements showed that the level of agreement between radon estimates obtained using the buffer and radon estimates from the regression model varied between 0.54 and 0.67 (Fig. 4). Comparing estimates from the buffer method with indoor radon values from measured houses we obtained ICC values between 0.63 and 0.68.

4 Discussion

Several methods for mapping of radon have been developed in recent years principally based on indoor radon measurements. Most of these studies have used different area sections such as municipal boundaries, postal codes and squares with different sizes to determine radon occurrence. Smethurst et al. (2006, 2008 and 2008b) compiled the geological and airborne radiometric data that this study is based on and they preformed similar comparisons of geology vs. indoor radon and uranium (e_{U}) in the ground and indoor radon with similar results. However, this study presents a more numerous data set of indoor measurement of radon, and uses the combined data set to assign a radon value to dwellings that lack radon measurement.

Comparable methods to what we present in this article have been described by Miles (1998a), and Miles and Appleton, (2005). They identify homes with high radon levels by inspecting geological combinations and indoor radon measurements within squares of 1 km × 1 km and 5 km × 5 km. Miles and Appleton, (2005) also used a kind of buffer method with no predefined limit to get at least 30 indoor radon measurements as basis for calculations of radon values that would be given to the whole square. In our study, over 70 % of the dwellings was based on measurements closer than 500 m from the actual dwelling. Since radon emissions from the ground can vary over short distances (Badr, 1993) and different geological boundaries (Hunter et al., 2009) we believe a short distance between estimated and measured dwellings is a more important factor than number of measured dwellings.

There are several benefits of using buffers to identify a dwelling's radon concentration. The method described here allows using a point (dwelling) as the center of the calculations of AM, GM and other statistical values. Since every home is the center for the calculations, this method will improve the exposure assessment and better take into account variations in radon concentration compared to a geographic area where all the homes are given the same radon values.

There are several geological factors such as radium content and permeability (Appleton and Miles, 2010; Sundal, 2007) of the ground that influence the radon level found in a building. By using our buffer method it is more likely that geological conditions are similar within the buffer. Over 70 % of the buffers used in this study had a radius between 300 and 500 m and each house was used as a midpoint for the calculations. This is in accordance with the hypothesis of Dubois (2007) that short-distance-scale correlation patterns express the same homogeneity in the house styles and living habits.

Another important factor on radon mapping is the misclassification that arises from allocation of indoor radon results to an incorrect geological unit, because the exact position of either geological boundary or the house is uncertain (Hunter et al., 2009). In our study each house address had a high accuracy of spatial location.

The production of modern radon-hazard maps requires accurate location data for each indoor radon measurement, but also equally important is the indoor radon-measurement density. In our study we had a high density of indoor measurements (Fig. 1) and were able to make calculations over short distances.

4.1 Testing of the model

Several studies recommend using radiometric measurements as an indicator of areas affected by radon (Duval and Otton, 1990; Appleton et al., 2011; Appleton et al., 2008; Scheib et al., 2006). We had detailed information for each dwelling in our data set allowing us to construct a regression model with radiometric data (e_{Th}, e_{U}) and bedrock geology found in each point. The radon values from radon measurements extracted from the buffer method were compared with radon values from the regression model by ICC.

According to Fleiss, (1986) ICC values below 0.4 indicates low agreement, values between 0.4 and 0.75 indicates fair to good agreement, and values above 0.75 indicate very good agreement. Our reliability test between radon estimates from buffers and radon estimates from the other methods must therefore be considered as showing a reasonably good agreement. Compared radon estimates from the buffer and radon estimates from the regression model show the lowest ICC value of 0.54 and highest ICC value of 0.67. Comparing estimates from the buffer method with indoor radon values from measured houses shows the lowest ICC value of 0.63 and highest ICC value of 0.68.

Buffers with 3–4 radon measurements ($n = 22\,214$) showed a low agreement when compared to radon values from the regression model (ICC = 0.04); when compared to real radon measurements a higher ICC value (0.79) was obtained. When we compared the estimates of radon from buffers with indoor radon measurements, a radon measurement from the dwelling was included in the calculation of the estimate of each buffer. This will affect the results, but this influence will, however, decrease as the number of measurements in the buffer increases.

The results showed some variation in ICC values when the data were broken down by population density, counties and number of radon measurements inside the buffer. Radon estimates from the model using airborne gamma ray spectrometry appeared to vary in relation to population density. We got the highest ICC values in sparsely populated areas. Appleton et al. (2008) have reported large variations in the concentrations of uranium in urban areas compared to rural areas. The most likely explanation for the variation is the uncertainty or the quality of gamma spectrometric data. Airborne measurements are performed using a gamma spectrometer linked to a detector mounted under an airplane or below a helicopter. The altitude varies between 50 and 120 meters depending on the area of flight, and the flight line spacing is between 100 and 500 m (Smethurst et al., 2006, 2008 and 2008b). The quality of the measurements will vary somewhat according to the altitude of flight and line spacing. In addition, urban areas have larger areas covered by asphalt and high buildings that will reduce the measuring response. The Oslo region is an area with low-level houses, 98.2 % of houses in all municipalities outside Oslo are detached, semi-detached and row houses. Oslo is a large city with mainly apartment buildings (15.5 %). This is a possible explanation of why the city of Oslo got some of the lowest ICC values.

4.2 Methodological limitations

Some factors that might influence the radon concentration were not available in our data set. Around 15.5 % of the buildings in the Oslo region are apartment blocks. Other factors such as building materials might affect radon levels in homes. However, Sundal et al. (2004) showed that building materials are less important in Norway than in other countries, probably because of a large element of timber, however differences can be observed for instance between coniferous and deciduous woods. We also lacked information regarding other factors such as levels of radon in household water, floor material and ventilation that also might affect the radon concentration in Norwegian dwellings.

5 Conclusions

The exposure assessment in an epidemiological study often depends of the type of data available. In the Oslo region we had indoor radon measurements in 6 % of the residential buildings. We also had information on bedrock geology and radiometric data. This allowed us to develop a buffer model where we used indoor radon measurements found around each dwelling to assign a radon value for homes lacking radon measurements. Radon values from buffers were compared to radon values from a regression model constructed with radiometric data, equivalent concentrations of thorium (e_{Th}), uranium (e_{U}) and bedrock geology; from which we found good agreement.

Over 70 % of the buffers had a radius between 300 and 500 m. By using the buffer method it is more likely that geological conditions are similar within the buffer and this may take more into account the variation of radon over short distances. There is also the probability that the short-distance-scale correlation pattern in Norway represents similar house styles and living habits. Although the method has certain limitations, we regard it as acceptable for use in later epidemiological studies.

Acknowledgements. This study was supported by the Agency for Health in the City of Oslo. Our thanks go to NRPA, Norway Digital, and The Geological Survey of Norway for accessible data on radon measurements and reference data on dwellings. We also thank The Geological Survey of Norway and Aashild Lysaker at Geodata AS for their assistance in building a GIS and to Magne Thoresen for statistical comments.

Edited by: F. Guzzetti
Reviewed by: M. A. Smethurst and one anonymous referee

References

Appleton, J. D.: Radon: sources, health risk, and hazard mapping, Ambio, 36, 85–89, 2007.

Appleton, J. D. and Miles, J. C.: A statistical evaluation of the geogenic controls on indoor radon concentrations and radon risk, J. Environ. Radioact., 101, 799–803, 2010.

Appleton, J. D., Miles, J. C., Green, B. M., and Larmour, R.: Pilot study of the application of Tellus airborne radiometric and soil geochemical data for radon mapping, J. Environ. Radioact., 99, 1687–1697, 2008.

Appleton, J. D., Doyle, E., Fenton, D., and Organo, C.: Radon potential mapping of the Tralee-Castleisland and Cavan areas (Ireland) based on airborne gamma-ray spectrometry and geology, J. Radiol. Prot., 31, 221–235, 2011.

Badr, I., Oliver, M. A., Hendry, G. L., and Durrani, S. A.: Determining the spatial scale of variation in soil radon values using a nested survey and analysis, Radiat. Prot. Dosim., 49, 433–442, 1993.

Dubois, G., Bossew, P., and Friedmann, H.: A geostatistical autopsy of the Austrian indoor radon survey (1992–2002), Sci. Total Environ., 15, 377–378, 2007.

Duval, J. S. and Otton, J. K.: Radium distribution and indoor radon in the Pacific Northwest, Geophys. Res. Lett., 17, 801–804, 1990.

Evrard, A. S., Hémon, D., Billon, S., Laurier, D., Jougla, E., Tirmarche, M., and Clavel, J.: Ecological association between indoor radon concentration and childhood leukaemia incidence in France, 1990–1998, Eur. J. Cancer Prev., 14, 147–157, 2005.

Faure, G.: Principles of Isotope Geology, second ed., John Wiley & Sons, ISBN: 0471864129, 1986.

Fleiss, J. L. (Ed.): The design and analysis of clinical experiments, Wiley, ISBN: 0-47-82047-4, ib. New York, S 7., 1986.

Gundersen, L. C. and Schumann, R. R.: Mapping the radon potential of the United States: examples from the Appalachians, Environ. Int., 22, S829–S837, 1996.

Health and Welfare: Survey of radon in Oslo 2008/2009 (in Norwegian).

Hulka, J., Fojtikova, I., Borecky, Z., Tomasek, L., Burian, I., and Thomas J.: Indoor radon risk mapping in the Czech Republic, Presented at the European Conference on Protection Against Radon at Home and at Work, Praha 10, National Radiation Protection Institute, Czech. Republic, 1997.

Hunter, N., Muirhead, C. R., Miles, J. C., and Appleton, J. D.: Uncertainties in radon related to house-specific factors and proximity to geological boundaries in England, Radiat. Prot. Dosim., 136, 17–22, 2009.

Hussain, S. P., Kennedy, C. H., Amstad, P., Lui H., Lechner, J. F., and Harris, C. C.: Radon and lung carcinogenesis: mutability of p53 codons 249 and 250 to 238 Pu alpha-particles in human bronchial epithelial cells, Carcinogenesis, Jan., 18, 121–125, 1997.

International Agency for Research on Cancer, IARC monographs on the evaluation of carcinogenic risksk to humans, Vol 78, Ionizing radiation, Part 2, Some internally deposited radionuclides, Lyon, France, 2001.

International Atomic Energy Agency (IAEA): Protection of the Public against Exposure Indoors due to Natural Sources of Radiation, DS421, April 2012.

Land Registry and Cadastre. Katverket. Om tildeling og forvaltning av adresser etter matrikkellova – adresseveileder, 2012 (in Norwegian).

Lappegår, T. and Nordvik, V.: Basement homes in the Norwegian housing market, ISBN: 82-536-0613-3, 1998 (in Norwegian).

Kendall, G. M., Little, M. P., Wakeford, R., Bunch, K. J., Miles, J. C., and Vincent, C.: A record-based case-control study of natural background radiation and the incidence of childhood leukaemia and other cancers in Great Britain during 1980–2006, Leukemia, 27, 3–9, 2013.

Kohli, S., Noorlind, B. H., and Löfman, O.,: Childhood leukaemia in areas with different radon levels: a spatial and temporal analysis using GIS, J. Epidemiol. Community Health, 54, 822–826, 2000.

Ménager, M. T., Heath, M. J., Ivanovich, M., Montjotin, C., Barillon, C. R., Camp, J., and Hasler, S. E.: Migration of uranium from uranium-mineralised fractures into the rock matrix in granite: implications for radionuclide transport around a radioactive waste repository. In: Fourth International Conference of Chemistry and Migration Behaviour of Actinides and Fission Products in the Geosphere (Migration 1993), Charleston, USA, 12–17 December 1993, Radiochim. Acta, 66/67, 47–83, 1993.

Miles, J.: Mapping radon-prone areas by lognormal modelling of house radon data, Health Phys., 74, 370–378, 1998a.

Miles, J.: Development of maps of radon-prone areas using radon measurements in houses, J. Hazard. Mater., 61, 53–58, 1998b.

Miles, J. C. and Appleton, J. D.: Mapping variation in radon potential both between and within geological units, J. Radiol. Prot., 25, 257–76, 2005.

Norwegian Radiation Protection Authority. Radon i inneluft. Helserisiko, målinger, mottiltak. StrålevernHefte 9, Østerås, 2008 (in Norwegian).

Norwegian Radiation Protection Authority. NRPA's new recommendations for radon in Norway. StrålevernInfo 25.09.2009 (in Norwegian).

Norwegian Radiation Protection Authority (NRPA). Radon i arealplanlegging. StrålevernInfo, 14, 12. ISSN 0806-895x, 23 August 2012 (in Norwegian).

Raaschou-Nielsen, O., Andersen, C. E., Andersen, H. E., Gravesen, P., and Schüz, J.: Domestic radon and childhood cancer in Denmark, Epidemiology, 19, 536–43, 2008.

Richardson, S., Monfort, C., Green, M., Draper, G., and Muirhead, C.: Spatial variation of natural radiation and childhood leukemia incidence in Great Britain, Stat. Med., 14, 2487–501, 1995.

Scheib, C., Appleton, J. D., Jones, D. G., and Hodgkinson, E.: Airborne uranium data in support of radon potential mapping in Derbyshire, Central England, in: Radon investigations in the Czech Republic XI and the 8th international workshop on the Geological Aspects of Radon Risk Mapping, edited by: Barnet, I., Neznal, M., and Pacherova, P., Prague, Czech. Geological Survey, 210–219, 2006.

Shrout, P. E. and Fleiss, J. L.: Intraclass correlations: uses in assessing rater reliability, Psychol. Bull., 86, 420–428, 1979.

Smethurst, M., Strand, T., Finne, T. E., and Sundal, A. V.: Airborne gamma ray spectrometer measurements and radon. The application of airborne gamma ray spectrometry in identifying radon prone areas – an analysis based on measurements in the Oslo region. Norwegian Radiation Protection Authority, StrålevernRapport 2006, 12, 2006 (in Norwegian).

Smethurst, M. A., Strand, T., Sundal, A. V., and Rudjord, A. L.: Large-scale radon hazard evaluation in the Oslofjord region of Norway utilizing indoor radon concentrations, airborne gamma ray spectrometry and geological mapping, Sci. Total Environ., 15, 379–393, 2008.

Smethurst, M, Sundal, A. V., Strand, T., and Bingen, B.: Testing the performance of a recent radon-hazard evaluation in the municipality of Gran, eastern Norway, in: Geology for Society, edited by: Slagstad, T., Geological Survey of Norway Special Publication, 11, 147–156, 2008b.

Statistics Norway. Table: 03175: Dwellings, by type of building (F), 2013 (in Norwegian).

Stigum, H., Strand, T., and Magnus, P.: Should radon be reduced in homes? A cost-effect analysis, Health Phys., 84, 227–235, 2003.

Strand, T., Aanestad, K., and Ruden, L.: Kartlegging av radon i 114 kommuner, Norwegian Radiation Protection Authority, 2001.

Stranden, E.: Radon in Norwegian dwellings and the feasibility of epidemiological studies, Radiat. Environ. Biophys., 25, 37–42, 1986.

Sundal, A. V., Henriksen, H., Soldal, O., and Strand, T.: The influence of geological factors on indoor radon concentrations in Norway, Sci. Total Environ., 26, 41–53, 2004.

Sundal, A. V., Jensen, C. L., Anestad, K., and Strand, T.: Anomalously high radon concentrations in dwellings located on permeable glacial sediments, J. Radiol. Prot., 27, 287–98, 2007.

Thorne, R., Foereman, N. K., and Mott, M. G.: Radon exposure and incidence of paediatric malignancies, Eur. J. Cancer., 32, 2371–2372, 1996.

Tong, J., Qin, L., Cao, Y., Li, J., Zhang, J., and An, Y.: Environmental radon exposure and childhood leukemia, J. Toxicol. Environ. Health., 15, 332–347, 2012.

Tzortzis, M. and Tsertos, H.: Determination of thorium, uranium and potassium elemental concentrations in surface soils in Cyprus, J. Environ. Radiact., 77, 325-338, 2004.

United Nations Scientific Committee on the Effects of Atomic Radiation, (UNSCEAR), Sources and effects of ionizing radiation 2000 Report to the General Assembly with Scientific Annexes, New York, United Nations, 2000.

Valmari, T. and Arvela H., and Reisbacka, H.: Radon in finnish apartment buildings, Radiation Protection Dosimetry, 152, 146–149, 2012.

Weaver, D. A., Hei, T. K., Hukku, B., McRaven, J. A., and Willey, J. C.: Cytogenetic and molecular genetic analysis of tumorigenic human bronchial epithelial cells induced by radon alpha particles, Carcinogenesis, 18, 1251–1257, 1997.

WHO handbook on indoor radon: a public health perspective/edited by: Zeeb, H. and Shannoun, F., ISBN 978-92-4-154767-3, 2009.

Working Group of the effort against radon. Arbeidsgruppen for samordnet innsats mot radon. Strategi for å redusere radoneksponering i Norge. (2007–2009) (in Norwegian).