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Prediction of indoor radon concentrations in dwellings in the Oslo region – a model based on geographical information systems

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Abstract

The purpose of this study was to develop a method to estimate the radon concentration inside each dwelling in the Oslo region, Norway.

The model was based on indoor radon measurements from dwellings at predefined distances from the unmeasured dwellings. The results were evaluated by comparing them with actual indoor measurements, airborne gamma ray spectrometry measurements and bedrock geology. It is the first study to evaluate the reliability between estimated indoor radon in each dwelling with airborne measurements (*e*K, *e*Th and *e*U) and underlying geology around the house in a large population.

A total of 28 396 indoor radon measurements showed that 42.2 % of the dwellings had a radon value higher than the threshold limit of 100 Bq m^{-3}. 18.9 % of the dwellings were above the maximum action level of 200 Bq m^{-3}.

A positive correlation was found between indoor radon concentration, bedrock geology and airborne gamma measurements (Pearson correlation: *e*K: 0.42, *e*Th: 0.67 and *e*U: 0.65). Highest correlation was found in areas with alum shale (*e*U: 0.74). Intraclass Correlation Coefficients (ICCs) showed a good agreement between radon estimates from our method and radon estimates from the regression model with ICC values between 0.54 and 0.67.

1 Introduction

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

The three naturally occurring radon isotopes, ^{219}Rn, ^{220}Rn and ^{222}Rn, are the main sources of background radiation exposing humans. Radon-222 is a naturally occurring radioactive gas resulting from the decay of uranium-238 which is the most common naturally occurring uranium isotope. Uranium is found in small quantities in all soils 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 short half-life; 3.96 and 55.6 s respectively, and are therefore not regarded as a health issue compared to ^{222}Rn (IAEA, 2012).

Uranium concentration in soil is calculated from measurements of gamma radiation. A study of the presence of alum shale in the central eastern parts of Norway showed a correlation between rock type and indoor radon concentration (Smethurst et al., 2011). 10 % of the homes built on alum shale had indoor radon concentrations above 1000 Bq m^{-3}. Similar studies from the UK also showed a correlation between the geology of the soil and radon concentrations in indoor air (Miles and Appleton, 2005).

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

Indoor radon concentrations vary and might be influenced by several factors, including the properties of the underlying geology (Appleton and Miles, 2010; Sundal et al., 2008), the permeability of the soil (Sundal, 2007) and several parameters relating to building materials and residents' lifestyles. In Norway, geology, ventilation system, 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 homes in Norway are built of wood (Sundal et al., 2004).

A growing number of studies are attempting to clarify the relationship between exposure to radon homes and the risk of cancer (Tong et al., 2012). Several studies on childhood cancer have developed predictive models of radon exposure (Kohli et al., 2000; Raasschou-Nielsen et al., 2008; Kendall et al., 2012). Some ecological studies are based on surveys of radon on the basis of only municipal boundaries and postal code (Richardson et al., 1995; Thorne et al., 1996; Evrard et al., 2005). Such a rough division might cover several geological units with different radon potential. Variations in geologic formations make the conclusions drawn for one area not necessarily valid in adjacent areas.

Kohli et al. (2000) based radon exposure on a map divided into radon exposure classes. The Swedish province Östergötland were divided into four risk areas in relation to the concentration of radon at ground level (high, possibly high, normal or low risk). Residential addresses of the child born in the area were linked to maps with information on risk exposure. The purpose was to determine the level of risk the child was exposed to at birth and during the study period.

Raasschou-Nielsen et al. (2008) based exposure on a mathematical model for radon exposure where the authors used geologic maps and 3120 indoor radon measurements to calculate exposure in 21 338 dwellings distributed throughout Denmark. A similar study by Kendall et al. (2012) in the UK used two sources to determine radon concentration. One was data from a national survey of indoor gamma radiation from natural background radiation based on measurements in 2283 houses. The model also used maps of radon potential for UK. Coordinates of the dwellings were allocated by postal code. Children's exposure was estimated from the mother's residence at child birth.

Several authors point out geology as a useful, but not sufficient 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) summarizes 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 dwelling, especially at lower radon levels.
- There may be uncertainty in the coordinates of both the dwelling and geological boundaries.

The purpose of this study was to develop a method to estimate the radon concentration inside each dwelling in the Oslo region. Results from this study will be used in a cancer study whose main purpose is to study a possible link between radon exposure, leukemia and brain cancer among children in the Oslo area, in south central Norway.

2 Materials and methods

2.1 The study area

This study includes all dwellings in four counties and 15 municipalities in the Oslo region. 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 and Søndre land, Ringerike, Hole, Lier, Nedre Eiker, Røyken, Drammen and Hurum. The Oslo region is an area of approximately 10 000 km^2. Almost two million people live there, representing around 40 % of the entire Norwegian population (Fig. 1).

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

The Norwegian Mapping Authority has through the Geographical Information System (GIS) access to coordinates of every Norwegian residence linked to its address. The coordinates are obtained from maps with scales 1 : 5000. The accuracy of the coordinates used in this study is within fem meters of the building center point. To estimate radon exposure in dwellings 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

2.2.1 Indoor radon measurements

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 2001–2010. 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). 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 % ($n = 830$) of the radon measurements were lacking address information and were excluded. The coordinates of the dwelling were obtained from the GAB registry which is a public registry of cadastral properties, addresses and buildings in Norway.

2.2.2 Data on the permeability of the soil and bedrock geology of the Oslo Region

The Geological Survey of Norway (NGU), in cooperation with the NRPA, produces maps showing potential radon exposure zones in the Oslo region. The dataset used in this survey includes information of bedrock geology. Bedrock geology was coded into four categories according to the uranium content in the different rock types: low, moderate, high and very high (Table 1). A more detailed description can be found in Smerthurst et al. (2008).

The permeability of the superficial deposits (Quaternary age) varies from impermeable clay to coarse gravel with high permeability. The masses are classified as described in Table 2.

2.2.3 Data on airborne gamma spectrometry measurements in the Oslo region

Mapping ^{40}K, ^{232}Th and ^{238}U in the Oslo region has been carried out by 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 centimeters depth. Based on the measurements NGU has prepared maps of equivalent concentrations of thorium (eTh), uranium (eU), and potassium (eK) (Fig. 2). A more detailed description of these studies is documented in Smethurst et al. (2008).

2.3 Prediction of indoor radon concentrations in dwellings

To estimate radon exposure in each dwelling GIS was used to digitize and integrate the information. 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.

2.3.1 A radon value to each dwelling

To estimate the radon levels to dwellings without measurements, the following steps were used and are illustrated in Fig. 4:

1. All dwellings sharing the same coordinate point as a dwelling with at least one measurement got the same radon value, or if more than one measurement, the average of all radon measurements was given to this coordinate point. The measure with the highest value in each coordinate point was used to construct buffers.
2. Around each remaining dwellings a buffer with 300 m radius were constructed (Fig. 4). 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 m were given AM and GM of the indoor radon measurements found in the buffer circle.
5. Dwellings with no radon measurements within a radius of 2000 m were giving the same radon value as the closest measured dwelling.

2.3.2 Statistical methods

Pearson 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. 26 310 of the dwellings had complete information on bedrock geology and ground permeability. Of these, 22 155 dwellings had complete information of isotopes *e*K, *e*Th and *e*U. In each buffer GM and AM was calculated for each of the isotopes ^{40}K, ^{232}Th and ^{238}U. In addition the percentage of radon measurements above 200 Bq m^{-3} was estimated.

These 22 155 buffers were also the basis for constructing a regressions model. Independent variables were: airborne radiometric measurement of *e*K, *e*Th, *e*U, bedrock geology (Table 1) and ground permeability (Table 2). A 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.

Further analyses were conducted with three different sets of data. The first data set was results of measurements in homes including; GM and AM of indoor radon measures, the percentage of radon measurements above 200 Bq m^{-3} and GM and AM of*e*K, *e*Th, *e*U was compared through Pearson correlation coefficient.

The second data set was the radon estimates based on the regression model. The third dataset 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 from measured dwellings. 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 originally introduced by Fleiss (1986), is generally used to asses agreement between two continuous variables and can interpreted as a measure of reproducibility or reliability. The agreement becomes important when comparing one method or instrument with another to see if they give equivalent results. In this study, ICC can be useful to use either from the point of view of 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 two-way mixed effects model for calculating the ICC values. SPSS software version 20 was used in all analysis.

3 Results

Totally, it was estimated radon values to 1 055 495 dwellings in the Oslo region. 83.8 % of the dwellings were located in urban areas.

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

53.7 % of the buffers had a radius of 300 m, 17.9 % had 500 m, 15.5 % had 1000 m and 13 % had a radius of 2000 m. 94.2 % of the dwellings had five or more radon measurements inside the buffer. 2.1 % buffers had 3–4 radon measurements. The distribution of measurements inside each buffer is shown in Fig. 5.

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}. 23.3 % of dwellings had a radon value between 100 and 200 Bq m^{-3}. 18.9 % of the dwellings were above 200 Bq m^{-3}. Analyses of the average value of radon in each coordinate shows 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}.

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

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

We used Person correlation coefficient to identify those independent variables with the strongest linear relationship to indoor radon measurements. From each buffer with originally radon measurements ($n = 22\,155$) we obtained values for both AM and GM. The best correlation was observed between GM of indoor radon measures and AM of eK, *e*Th and *e*U. GM of indoor radon measures, 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 *e*K, *e*Th and *e*U we used AM because these data was closer to normal distribution.

Pearson correlation coefficient between GM of indoor radon measures found within the buffer containing 20 or more measures ($n = 9405$) 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 buffer with 30 or more radon measurements was 0.72.

Pearson's correlation coefficient between GM of indoor radon measures found within the buffers containing 20 or more measures and AM of *e*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 *e*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, *e*K and*e*U) and bedrock geology. Stepwise regression indicated that *e*K and *e*Th were less significant 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 large number of houses lacked permeability data.

3.2 Reliability of the results

It was of interest to evaluate the reliability of the results obtained from the buffer method. 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 had 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 direct in the dwellings. These three continuous measurements were compared for analyzing the degree of agreement between them. It means how much the radon value from the buffer method agrees with the others 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. 6). Comparing estimates from the buffer method with indoor radon values from measured houses we obtained ICC values between 0.63 and 0.68.

ICC improved when the dataset was split in two according to population density. We observed ICC values in sparsely populated areas between 0.42 and 0.76. For densely populated areas ICC varied between 0.52 and 0.63.

ICC values in the three largest counties covered by the study showed similar trends in relation to population density. The county of Østfold had the highest ICC. The city of Oslo had the highest variation in ICC values, from below 0.11 in densely populated areas and up to 0.80 in sparsely populated areas.

4 Discussion

There are several benefits of using buffers to identify a dwellings 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 better take into account variations in radon concentration compared to a geographic area where all the homes are given the same radon values.

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. Similar 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 a square of 1 km × 1 km and 5 km × 5 km. Miles and Appleton (2005) used also a buffer method with not limit radius to get at least 30 indoor radon measurements as basis for calculations of radon values that would be given to the whole square. This might give that the same measurements are used on at quite large geographical unit. In our study over 70 present 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 short distance between estimated and measured dwellings is a more important factor than number of measured dwellings.

There are several geological factors such as radium content and permeability of the ground that influences the radon level found in a building. By using our buffer method it is more likely that geological conditions are similar within the buffer compared to earlier studies. 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 pattern express the same homogeneity in the house styles and living habits.

Another important factor on radon mapping are when misclassification arise 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 N 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 indoor radon measurements densities. In our study we had high density result measurements in the houses and were available to make calculations over short distances.

4.1 Testing of the model

A positive correlation was found between indoor radon concentration, bedrock geology, and airborne gamma measurements. Although this observation is consistent with previous findings (Scheib et al., 2006), the use of detailed information in our dataset allowed us to characterize, to our knowledge for the first time, the association between predicted indoor radon concentrations in each dwelling, in a region with a population size of nearly two million, and radiometric measurements bedrock and superficial geology at the same location.

Several studies recommend using radiometric measurements as an indicator of the areas affected by radon (Duval and Otton, 1990; Appleton et al., 2008, 2011). Scheib et al. (2006) concludes that regression models including *e*K, *e*Th, *e*U and permeability are important in predicting radon.

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 (lowest ICC value = 0.42 and highest ICC value = 0.80).

Buffers with 3–4 radon measurements ($n = 22\,214$) showed a low agreement when compared with radon values from the regression model (ICC = 0.04). When we compared them with real radon measurements a higher ICC values (0.79) as 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. This influence will, however, decrease as the number radon measurements in the buffer increase.

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. 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 quality of gamma spectrometric data. Airborne measurements are performed using a gamma spectrometer linked to a detector mounted in or below a helicopter. Lowest altitude varies between 50 to 250 m depending on the hights of area's buildings. The quality of the measurements will probably change when the detector height is 250 m in urban areas instead of around 50 m in the countryside. In addition, urban areas have larger areas covered by asphalt and buildings. The gamma-ray spectrometry has the ability to penetrate ca. 40 cm of the ground and will in urban areas most likely not reflect natural radiation. This is a plausible explanation why the city of Oslo got some of the lowest ICC values.

4.2 Methodological limitations

This study has some limitations as well. Some factors that might influence radon concentration were not available in our dataset. Around 35 % of the units 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. We also lacked information regarding other factors as floor material and ventilation that also might affect the radon concentration in Norwegian dwellings.

5 Conclusions

- A model has been developed for estimating radon exposure inside homes in the Oslo region.
- There was a wide geographical variation in the occurrence of indoor radon in the homes in the Oslo area. This is reflected when we analyze the maximum value of radon found at each coordinate; 42.2 % of the dwellings had a radon concentration higher than the threshold limit of 100 $\mathrm{Bq\,m^{-3}}$, 23.3 % was between 100 and

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200 Bq m^{-3}, and 18.9 % of the dwellings were above the maximum threshold level of 200 Bq m^{-3}.

- A positive correlation was found between the GM of indoor radon, bedrock geology, and AM of *e*K, *e*Th and *e*U. GM of indoor radon measurements and AM for *e*U in areas with alum shale showed the highest correlation (0.74). Correlation between the percentage of radon measurements above 200 Bq m^{-3} and AM of *e*U was 0.72. Correlation coefficient between GM for radon and AM of *e*K, *e*Th and *e*U was 0.42, 0.67 and 0.65 respectively.
- This is the first study to evaluate the reliability between predicted indoor radon in each dwelling, in a region of this size, with radiometric measurements and geology.
- There was a good agreement between radon estimates from the buffer method and radon estimates from the regression model with ICC values between 0.54 and 0.67. ICC improved when dataset was split in two according to population density ICC between 0.42 and 0.76.
- Although the method has certain limitations, we regard it as acceptable for use in epidemiological studies.

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Table 1. Bedrock geology in the Oslo region categorized by uranium content.

Bedrock geology	Category
Alum shale	Very high
Granites and rhyolite	High
Monsonitter, latitter, syenite and trakytt	Moderate
Gneiss, dark intrusive and sediments	Low

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Table 2. Annual average indoor radon concentrations over 200 Bq m^{-3} in homes surrounded different superficial deposits.

Drift geology	% ≥ 200 Bq m^{-3}	Number of observations
Moderate permeability	20 %	4318
High permeability	12 %	927
Low permeability	8 %	1440
Bedrok/thin cover	12 %	1316
Anthropogenic fill	6 %	939

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

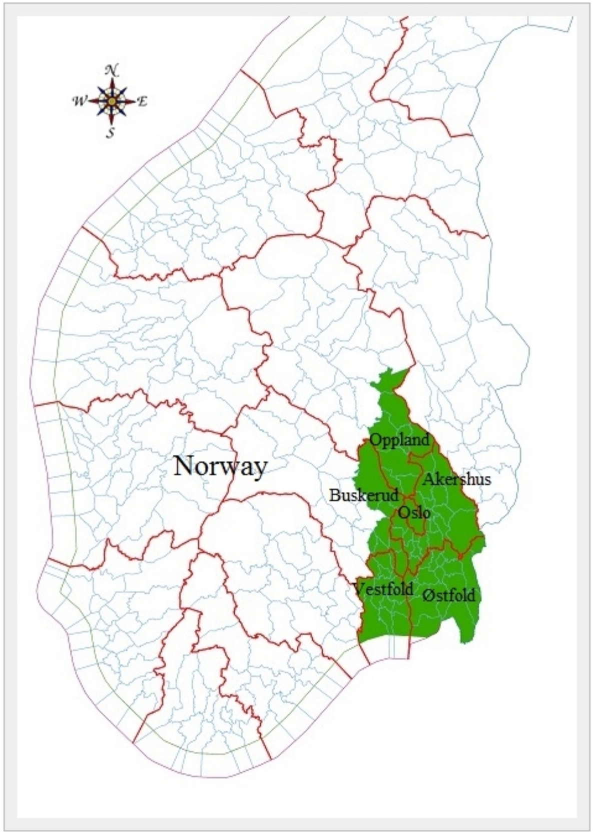

Fig. 1. The study region in south central Norway contains four counties, altogether fifteen municipalities, and is referred to as the Oslo region in this study.

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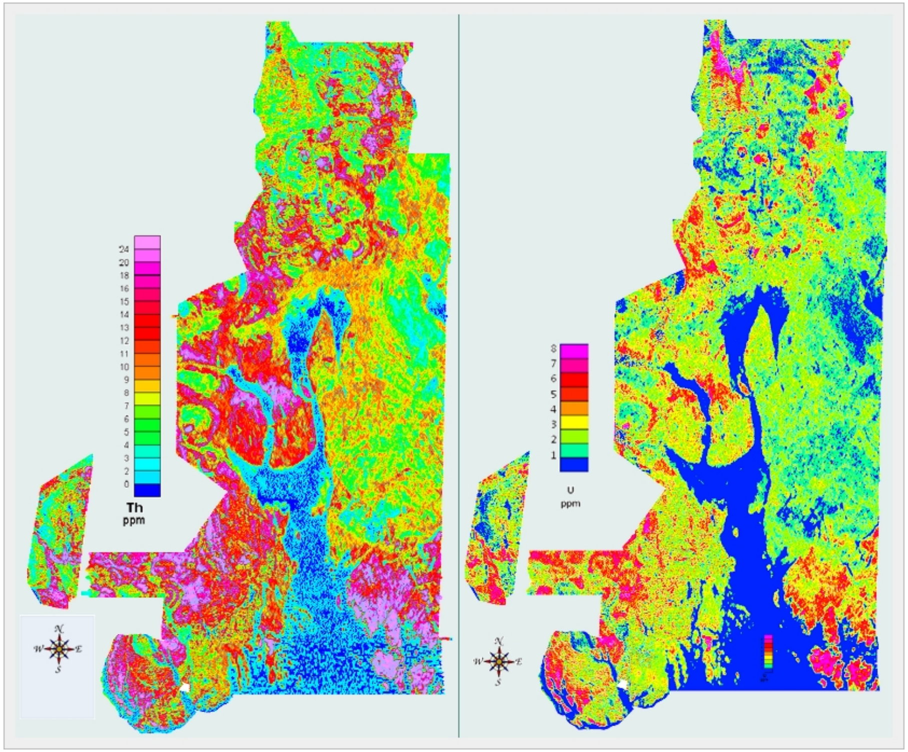

Fig. 2. Thorium and uranium concentrations based on gamma ray spectrometer surveys for the Oslo region by airborne gamma-ray spectrometry. Surveys were carried out from 1981 to 2003 by the Geological Survey of Norway.

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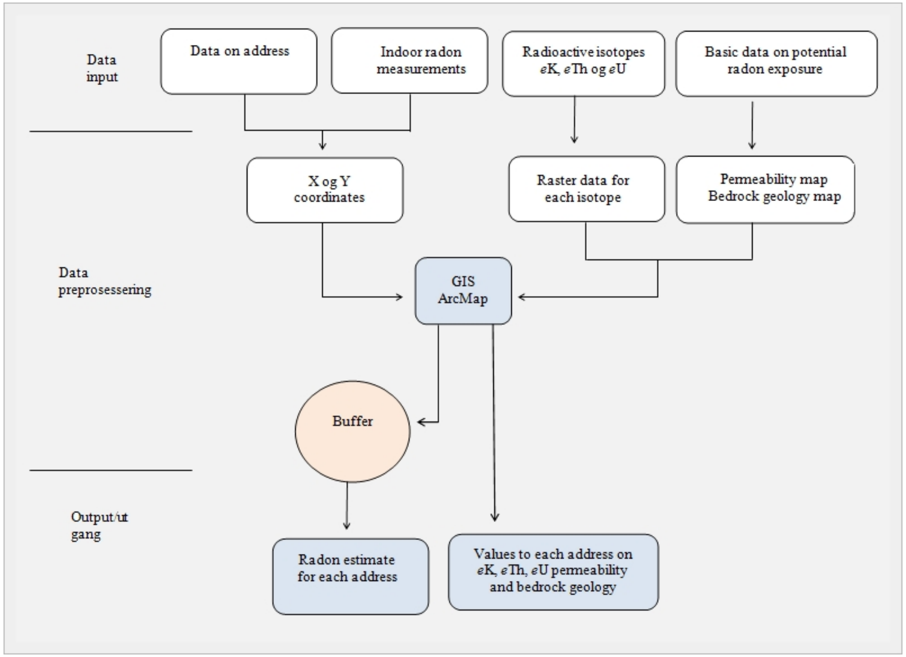

Fig. 3. Flow chart illustrating the data analysis and integration methodology.

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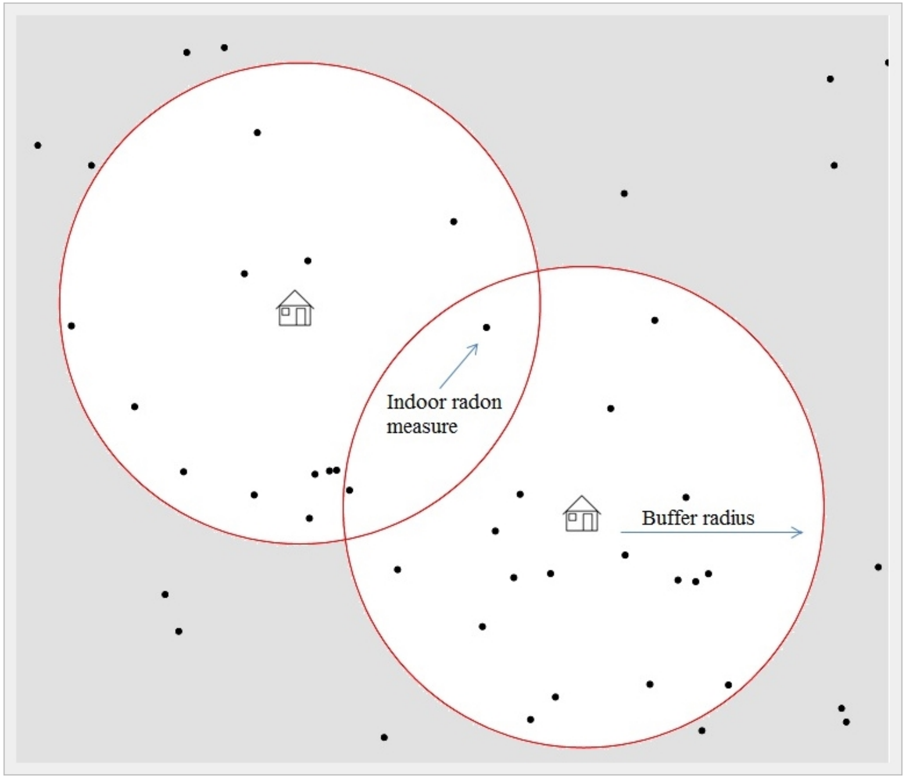

Fig. 4. The relationship between buffer, dwelling and indoor radon measurements. The house in the center represents a dwelling without radon value and the red circle is the associated buffer.

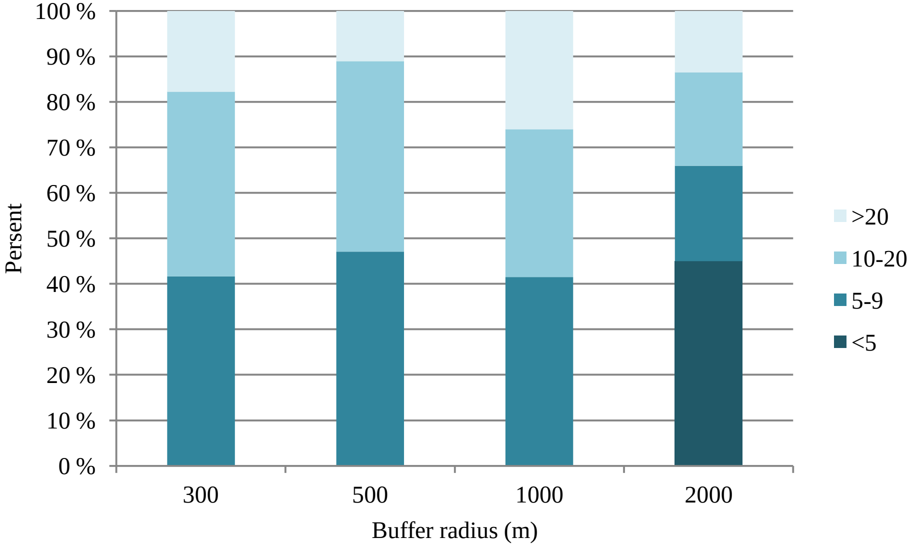

Fig. 5. Number of radon measurements by buffer size in the Oslo region 2001–2010.

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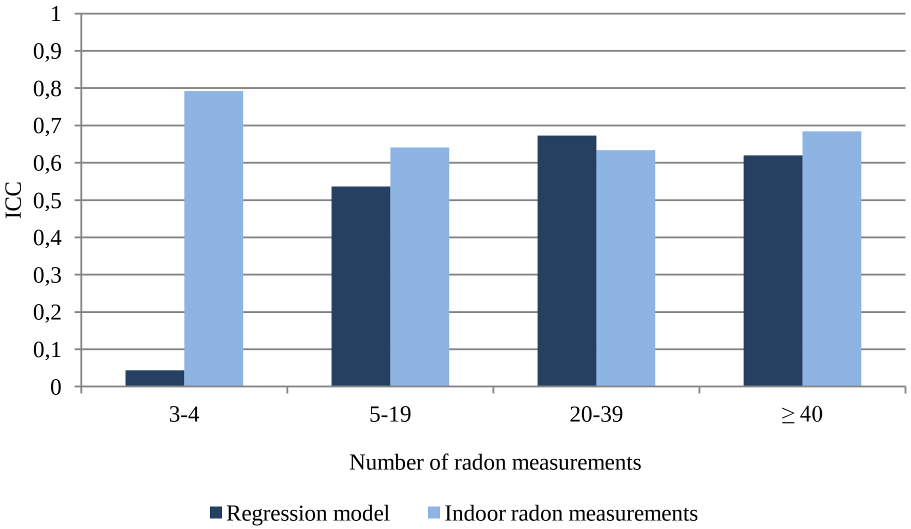

Fig. 6. Comparison of ICC values between estimates of radon from the buffer method, regression model and indoor radon measurements, distributed by the number of radon measurements in the buffers.