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A SOFTWARE FOR INDOOR RADON
RISK MAPPING BASED ON GEOLOGY

by

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A computer code dedicated to indoor radon risk mapping is presented, based on geology and on indoor radon measurements. Assuming a lognormal distribution of the data at the local scale, it provides the estimation of the percentage of houses above a chosen reference level, at the points of a grid specified by the user, using the moving average of data belonging to the same geological unit as the grid point.

Key words: radon mapping, radon geostatistics

INTRODUCTION

The indoor radon concentration is the product of many factors which are often not known or badly known, many of which can be considered as random factors when trying to predict the level of radon risk at a given place. A milestone in radon risk studies is the multivariate analysis of the long-term indoor data gathered in the UK, published by Appleton and Miles [1]. This report showed that the main factors influencing the indoor radon concentration are the geological context, and the geographical co-ordinates within a given context, other factors having a much weaker influence on the variability of time-averaged indoor radon. This provides the basis of the methodology of indoor radon risk mapping used in UK, in which the geological context is fully taken into account.

Among the many possible risk indicators, the most popular is the percentage of houses having a radon concentration higher than a chosen reference level. This number can indeed be well understood by the population, and is thus adequate for the dissemination of the information. At a local scale, the available data are often too scarce to allow for a direct calculation of this percentage, and it is a common approach to evaluate it from an assumed local statistical distribution of the data, using Geostatistics to predict the local parameters of this distribution like its mean and its standard deviation. Indoor radon approximately follows a lognormal distribution [2], as expected from the central limit theorem for a product of many random factors. It will thus be convenient to use the logarithm of the radon concentration as the data, and the logarithmic mean (LM) and logarithmic standard deviation (LSD) to characterize the distribution.

Kriging is a well-known geostatistical method [3] which gives the "best" prediction of the local distribution of the data. It is a smoothing interpolator, making a weighted average of the data available in a chosen local neighbourhood. The variogram is used to evaluate the strength of spatial correlations between the data. If they are correlated, the closest data receive more weight in the average. With no spatial correlation, kriging is equivalent to a moving average with constant weight.

In our earlier works, all these points were examined for the radon database available for the Walloon region in Belgium, and a risk map was produced [4]. In this work, we used several commercial programmes like EXCEL, SURFER, and other. A significant part of the work was to organize the transfer of data from one programme to the other, and a lot of it had to be repeated when including new data, or when redefining some of the geological units used for the map. We found it much easier for the future updates of the map to have a dedicated computer code doing exactly what we want, and which could also be used by other groups. This computer programme is presented in the present article. For the sake of completeness, the methodology will be briefly recalled, with a few recently added points.

METHODOLOGY

Simplified geology

Our radon map is based on the Belgian geological map, which is available in numerical form [5].

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Such maps are available in most European countries, but with different degree of inclusion of the useful information, which should not only include the age of the geological formation, but also the lithology. The presence of a superficial cover is not always known. Therefore the way of defining the useful geological units will vary from one country to the other. Moreover, geostatistics can only be applied within a geological unit if enough data are available for this unit. According to the sampling density, it can be necessary to group different formations in a common geological unit. Of course, they should only be grouped if they present similar levels of radon risk. How these groups are defined can thus differ according to the country, depending on the local geology, but also on the available radon data. In the application to the Walloon region, we started from the classification used in the OneGeology map [6], grouping formations with similar ages and similar level of indoor radon risk, ending with 17 units: Lower-Middle Cambrian in the Brabant massif, other Cambrian, Ordovician, Silurian, Lower Devonian, Middle Devonian, Upper Devonian, Tournaisian, Visean, Silesian, Permian, Trias, Jurassic, Cretaceous, Tertiary, Quaternary loess, and Alluvia of valleys.

The software could be used for mapping any other variable strongly related to geology. It could also be used to produce maps based on information other than geology which can be specified at each geographical position. These extensions of its use will however be limited to variables having a normal or a log-normal distribution.

Lognormal distribution

In a preceding work [7] we presented a discussion on the best way to use the lognormal distribution in indoor radon risk mapping. The main conclusions were:

– Several sources of inaccuracy on the low-concentration data may induce strong deviations from the lognormal trend in the "left-hand" low-value tail of the distribution. These data should have no influence on the risk indicator (percentage of data above the reference level), and it is better not to consider them, by only using the "right-hand" upper part of the distribution, *i. e.*, data higher than the median.

– There can be significant deviations from the lognormal trend in the high-value tail too. However, the deviation generally occurs above the reference level, and only has a small influence on the calculated percentage above this level.

– When calculated for local samples (the 20 nearest data), the logarithmic standard deviation LSD(20) shows strong statistical variations which bear no actual information. It is better to use a constant LSD for the whole geological unit, which is the average of local LSD(20) on this unit (see [8] for a different approach).

With our software, the user will be allowed to choose between the four options for the distribution: log-normal, log-normal restricted to the "right-hand" part, normal, normal restricted to the "right-hand" part, the latter two being available for mapping variables other than radon.

Variograms and geostatistical method

The variograms of the data collected in the Walloon region were examined for different geological units GU in [4] generally showing quite weak spatial correlations, the results being almost compatible with a constant variogram. This justifies the choice of the moving average as an appropriate mapping method.

The moving average is applied at a given location (x_0, y_0) to the N nearest data associated to the same geological unit GU as the one found at (x_0, y_0). It is applied to the logarithm of measured indoor concentrations $LC(x, y, GU)$, and it is used either to calculate the local logarithmic mean $LM(x_0, y_0)$ or the local median.

Two variants are considered for estimating the local percentage above the reference level

– Variant LN: the local lognormal parameters $LM(x_0, y_0)$ and $LSD(x_0, y_0)$ are calculated with all N data of the local sample.

– Variant RL: the local median is calculated for the local sample of N data and assumed to be equal to $LM(x_0, y_0)$, and only the "right-hand" upper half of the distribution is used to evaluate $LSD(x_0, y_0)$.

In both options, the local LSD is averaged for the GU. The percentage above the reference level is then calculated for the lognormal distribution characterized by $LM(x_0, y_0)$ and the average LSD.

Short-term *vs.* long-term measurements

A special situation occurs in the Belgian indoor radon database: the inclusion of short-term ST measurements using charcoal canisters, together with long-term LT track-etch measurements. The database considered here contains ground floor measurements and covers the Walloon region with an average density of approximately 1 data per km². The two data sets have been collected by the Federal Agency for Nuclear Control (FANC) on one hand, and by the Institut Superieur Industriel de Bruxelles (ISIB) on the other hand. The ISIB data, about 5 000, are short-term measurements collected between 1990 and 2005 in houses with charcoal canisters exposed during 3-4 days in every season except summer. Their distribution follows roughly the population density. The FANC data, about 13 700 in 2012, are long-term data collected using

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track-etch detectors, exposed for 3 months, from 1995 to present, and are more strongly concentrated in radon-affected zones. More detail on the database can be found in our previous works [4, 9]. Because the two sets of data are complementary from the geographical point of view, it is necessary to try to include the ST data, despite their higher variability. Their inclusion is based on two considerations:

– ST data and LT data are statistically equivalent for the evaluation of LM [9], and
– assuming that the time variability of ST data is independent of the GU, we correct the average variance of ST data on a given GU [4]

$$LSD_{corr}^2 \quad LSD_{ST}^2 \quad LSD_{time}^2$$

before including it in the calculation of the global average LSD for the GU, N_{ST}, and N_{LT} being the number of ST and LT data on this GU

$$LSD^2(GU) \quad \frac{N_{ST}\ LSD_{corr}^2 \quad N_{LT}\ LSD_{LT}^2}{N_{ST} \quad N_{LT}}$$

LSD_{time}^2 is the average on all GU of $(LSD_{ST}^2 \quad LSD_{LT}^2)$.

RADON MAPPING SOFTWARE

General information

The indoor radon mapping software is provided as a DOS executable code, the source code being written in FORTRAN95. Input files, to be provided by the user, are text files described below. The execution provides output text files and optionally colour maps as BMP file. Potential users may freely obtain the code by writing to the corresponding author.

Input files

List of geological units. The file gives the number of GUs (Line 1) and one GU code of 3 characters per line.

Database. The file gives the number of data records, and one record per line including a reference number, the *x* and *y* coordinates, the radon concentration, the measurement term (LT or ST), and the geological unit at this house.

Grid for the map. The file gives the number of grid nodes, and their list (one node per line) with the coordinates *x* and *y*, and the geological unit at this node.

Options. This file gives various optional parameters:

– type of distribution (lognormal, right-hand lognormal, normal, right-hand normal),

– number *N* of nearest data to include in the local sample for the moving average,
– maximum radius *R* of the local sample; if less than *N* data are found within a distance *R*, the node is excluded from the calculation,
– type of dataset (LT only, ST only, mixed),
– reference radon level used in the risk indicator (% above the reference level),
– names of image files generated (see output files) and spacing of the grid nodes,
– lower and upper concentration thresholds for the mean/median map colour scale,
– names of the 3 input files described above,
– names of the 3 output files described below, and
– title or short reference.

Output files

Results. This file gives the calculated results for each grid node, together with some of the data: co-ordinates *x* and *y*, logarithmic mean or median, percentage above reference level, radius of the local sample (reflects the local sampling density), geological unit. In general, it is expected that the user will use these results with his favourite GIS.

Statistics. The file gives for each geological unit: the number of data, separately for LT and ST, the number of grid nodes, the average LT and ST LSD, and the global average LSD as defined in §2.4. Average LSD are only calculated for the GU when at least 10 grid nodes in the GU have a valid local sample (*i. e.* N data within a distance less than R).

Journal. This file reproduces the options and lists the "error" messages, giving in particular the list of nodes for which the local sampling has too few data, and the list of the GU for which the LT + ST mixing is not accomplished.

Map files

Two BMP image files can be produced as an option: a map of the logarithmic mean or median, and a map of the percentage above the reference level. The maps can only be produced when the grid nodes are regularly spaced along x and y, with a maximum of 1000 1000 nodes.

Map of the mean/median. According to the type of distribution chosen in the options, the image will display a colour map of the values of the mean (normal), the median (right-hand normal), the logarithmic mean (lognormal) or the logarithmic median (right-hand lognormal). 14 colour levels are used, the user must specify, in the options, the lower threshold (between levels 1 and 2) and the upper threshold (between levels 13 and 14). These thresholds are expressed as concentration levels, even if the lognormal distribution is used. The grey colour is used for the nodes with too few data.

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Map of the percentages above the reference level. In this image the colour scale displays the decimal logarithm of the predicted percentage of houses above the chosen reference level, with 4 colour levels under 1%, 5 from 1% to 10%, and 5 from 10% to 100%. The grey colour is used for the nodes with too few data.

Figure 1 shows the map of percentages for the Walloon and Brussels regions in Belgium, using the most recent version of the database. The options are: right-hand lognormal, 20 data within a radius of 25 km, mix of LT and ST, reference level 400 Bq/m^3, 1 km   1 km grid. (The grey scale used here for BW printing, using black for nodes with too few data, is not the colour scale normally produced by the code).
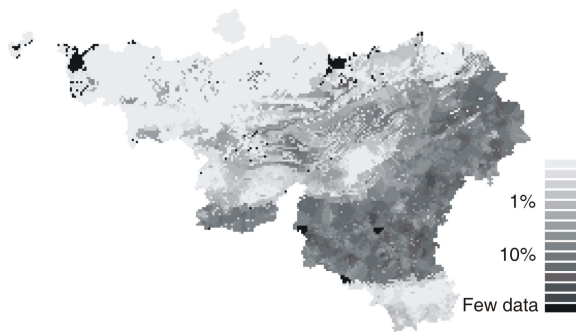

Figure 1. Map of percentage for the Wallon and Brussels regions

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AUTHOR CONTRIBUTIONS

The methodology of indoor radon risk mapping was initially devoloped by G. Cinelli and perfected by both authors in collaboration. The computer code was written by F. Tondeur who wrote the manuscript.

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Франсоа ТОНДЕР, Ђорђа ЧИНЕЛИ

ПРОГРАМСКИ ПАКЕТ ЗА МАПИРАЊЕ РИЗИКА ОД РАДОНА У ЗАТВОРЕНОМ ПРОСТОРУ ЗАСНОВАН НА ГЕОЛОГИЈИ

У овом раду приказан је програмски пакет за мапирање ризика од радона у затвореном простору заснован на геологији и мерењима радона у затвореном простору. Претпостављајући лог-нормалну расподелу података у локалној размери, програмски пакет процењује проценте кућа изнад изабраног референтног нивоа, у тачкама мреже коју изабере корисник, користећи променљиви просек података који одговарају истим геолошким јединицама као мапиране тачке.

Кључне речи: мапирање радона, геостатистика радона