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Variance of indoor radon concentration: Major influencing factors

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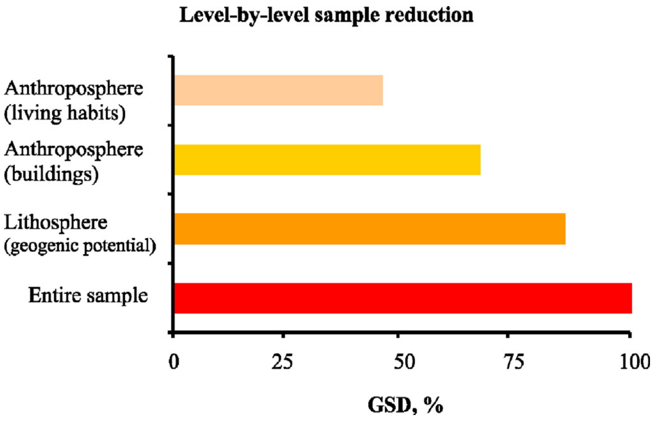
HIGHLIGHTS

- Influence of lithosphere and anthroposphere on variance of indoor radon is found.
- Level-by-level analysis reduces GSD by a factor of 1.9.
- Worldwide GSD is underestimated.

GRAPHICAL ABSTRACT



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ABSTRACT

Variance of radon concentration in dwelling atmosphere is analysed with regard to geogenic and anthropogenic influencing factors. Analysis includes review of 81 national and regional indoor radon surveys with varying sampling pattern, sample size and duration of measurements and detailed consideration of two regional surveys (Sverdlovsk oblast, Russia and Niška Banja, Serbia). The analysis of the geometric standard deviation revealed that main factors influencing the dispersion of indoor radon concentration over the territory are as follows: area of territory, sample size, characteristics of measurements technique, the radon geogenic potential, building construction characteristics and living habits. As shown for Sverdlovsk oblast and Niška Banja town the dispersion as quantified by GSD is reduced by restricting to certain levels of control factors. Application of the developed approach to characterization of the world population radon exposure is discussed.

1. Introduction

Radon in the residential indoor environment has been acknowledged a significant health risk factor (WHO, 2009 for a summary). As a consequence, increasingly one attempts to regulate it by establishing reference levels and radon action plans aimed to reduce or limit exposure to radon. A latest example is the European Basic Safety Standards (European Council, 2014). One task included in radon action plans is estimating the geographical distribution of indoor radon concentrations in residences or workplaces, or of physical quantities, which control the concentration, such as the radon potential, and others. The purpose of

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spatial modelling is visualizing the geographical distribution, but also prediction at un-sampled locations. Maps can serve for optimizing and prioritizing the allocation of resources, in terms of denser surveys, prevention and mitigation of radon exposure.

The main obstacle is the high spatial variability of radon related quantities also at detailed scale. It implies that estimating the mean over a given spatial unit with reasonable precision requires a high number of samples, and that prediction is highly uncertain. If, on the other hand, one has a prior idea of the spatial distribution, such prediction can be simplified. Indeed, this has been used for estimating local risk, defined as probability to exceed a reference level, by a number of authors. For example this is the standard method on which radon maps rely in the U.K., e.g. Miles (1994), and many subsequent articles. Also in the US, the lognormal assumption has been used for mapping, including more sophisticated methods of Bayesian parameter estimation, e.g. Price et al. (1996); similarly for Demark, Andersen et al. (2001). More recently, the method has been applied in Belgium, Cinelli et al. (2011).

Formally, if one can estimate the distribution of a quantity Z, $F_Z(z;\theta)$, where θ is the vector of parameters which characterizes the distribution, that probability equals prob.$(Z > z') = 1 - F_Z(z';\theta)$. The task reduces to estimating θ, which can be less data expensive than estimating the risk from the data only, with similar accuracy.

Being able to estimate the distribution of radon quantities is essential for planning surveys, i.e. in a situation where no or few data are available. The reason is, like discussed above, that estimating a statistic within a spatial unit (municipality, grid cell, etc.), such as the mean or an exceedance probability with given tolerable uncertainty requires a certain minimal number of samples. The number of samples, estimated by anticipating a distribution, is a centrally important input to the design of a sampling survey.

Regarding the physical source of the problem, the dispersion of indoor radon concentrations in a sample of dwellings depends on the variability of physical conditions, which control radon accumulation in a dwelling, and on their spatial covariance structure. The conditions, in turn, depend on a number of factors such as geographical extension of the survey, variety of house construction and dwelling types and living habits.

Considerable amount of national and regional indoor radon surveys was conducted during last decades. A large database for spatial radon statistics is the one underlying the European indoor radon map (Dubois et al., 2010, Tollefsen et al., 2014, Demoury et al., 2013, Gruber et al., 2013), currently (end 2014) comprising about 800,000 individual measurements. Several reviews of radon survey results are available (Bossew, 2010; UNSCEAR, 2006; Dubois, 2005; UNSCEAR, 2000; UNSCEAR, 1993, among others). In many cases, it has been noted that the indoor radon concentration within the surveyed territory can be reasonably well approximated by a lognormal distribution. Theoretical reasons for this behaviour have been discussed in the literature (Cinelli and Tondeur, 2015, Daraktchieva et al., 2014, Bossew, 2010, Murphy and Organo, 2008), but no entirely convincing solution seems to exist so far. While the lognormal distribution is by far the most popular one for radon modelling, also others have been proposed. For example, Murphy and Organo (2008) recommend the beta distribution. Tuia and Kanevski (2007) remarked that while the lognormal distribution is appropriate for “the bulk” of data, it might fail in describing the upper tail, for which they suggest an extreme value distribution. The resolving the “lognormal mysticism” (Tóth et al., 2006; Hámori et al., 2006) is not the objective of this paper; instead, we attempt to investigate the “lognormal effect” based on empirical evidence.

The aims of this paper are to suggest a procedure to analyse the heterogeneity of the sample of radon surveys and to find typical values of the GSD of residential indoor radon concentration over a territory, which is a convenient measure of dispersion for skew distributed quantities, in dependence of geographical area and influencing factors. For this purpose, univariate analyses of large number of radon surveys were performed.

2. Materials and methods

The lognormal distribution is exhaustively characterized by two parameters: the geometric mean (GM) as location and the geometric standard deviation (GSD) as dispersion measures. If one knows, or has good reasons to assume that an observed quantity is approximately lognormal distributed, GM and GSD are therefore reasonable choices for characterizing the distribution of the quantity. Formally, GM and GSD can of course always be calculated, whether the lognormal condition holds or not.

Shortly summarize the properties of the lognormal distribution. A quantity Z being distributed lognormal, $Z \sim LN(GM,GSD)$, is equivalent to $\ln(Z) \sim N(\mu,\sigma)$ (normal distribution) with $\mu = \ln(GM)$ and $\sigma = \ln(GSD)$. The expectation or arithmetical mean, AM, equals $AM = GM\ \exp.(\sigma^2/2)$, coefficient of variation, $CV = SD/AM$, $CV = \sqrt{(\exp(\sigma^2) - 1)}$, SD the standard deviation. Empirical GM and GSD of a sample are therefore most easily calculated as exp. of AM and SD of the ln(Z). However, one has to be aware that some statistics computed this way are biased estimates of an anticipated true lognormal distribution of the data. One can show that GSD estimated as exp.(SD(ln(Z))) is nearly unbiased while the empirical GM, estimated as exp.(AM(ln(Z))) systematically underestimates the true one. The AM of the sample is always an unbiased estimate of the expectation (the true mean) due to the central limit theorem (This holds as long as the independent and identically distributed condition is fulfilled, which is not the case in the presence of spatial autocorrelation), but not so the SD. An alternative is fitting a lognormal distribution and deriving the parameters from that fit.

2.1. Review of national and regional radon surveys

Combined analysis of 81 national and regional indoor radon surveys was conducted and dependence of GSD on various factors was studied. Analysis includes results of UNSCEAR reviews made for reports 1993, 2000 and 2006. Also, data for the analysis were taken from publications and other sources which are not included in the UNSCEAR reports (Celebi et al., 2014, Epstein et al., 2014, Kropat et al., 2014, Quarto et al., 2013, Tuia and Kanevski, 2007, Kies et al., 1996). The following information was considered: country or region, arithmetic mean, geometric mean, maximum value, GSD, duration of exposure, number of surveyed dwellings. For 48 surveys entire information was gathered.

For the analysis of these data, we estimated average GSD and standard error in the sub groups as follows:

- two groups by arithmetic mean (above and below 40 Bq/m^3);
- two groups by duration of exposure of radon measurements devices (above and below 180 days);
- two groups by area of surveyed country or region (above and below the median value of 120,000 km^2); and
- two groups by number of surveyed dwellings (above and below 1000).

2.2. Special analysis of raw data of radon surveys in Sverdlovsk oblast, Russia and Niška Banja, Serbia

The Radon survey in Sverdlovsk oblast, one of the biggest regions of Russia (population 4.4 million, area 200,000 km^2,) has been conducted in the period from 1992 to 2000 (Yarmoshenko et al., 2002) and in Ekaterinburg (population 1.4 million), capital city of the Sverdlovsk oblast in the period from 2005 to 2008 (Yarmoshenko et al., 2010). The radon concentrations were measured by LR-115 Kodak type 2 track detectors in approximately 400 and 3000 dwellings in Ekaterinburg and other sites of oblast, respectively. Radon detectors were installed in the living room or bedroom for 2–3 months. Annual indoor radon concentrations were estimated applying results of a special study about the seasonal variation of indoor radon (Onishchenko et al., 2013).