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The uncertainty in the radon hazard classification of areas as a function of the number of measurements

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A B S T R A C T

The administration in many countries demands a classification of areas concerning their radon risk taking into account the requirements of the EU Basic Safety Standards. The wide variation of indoor radon concentrations in an area which is caused by different house construction, different living style and different geological situations introduces large uncertainties for any classification scheme. Therefore, it is of importance to estimate the size of the experimental coefficient of variation (relative standard deviation) of the parameter which is used to classify an area. Besides the time period of measurement it is the number of measurements which strongly influences this uncertainty and it is important to find a compromise between the economic possibilities and the needed confidence level. Some countries do not use pure measurement results for the classification of areas but use derived quantities, usually called radon potential, which should reduce the influence of house construction, living style etc. and should rather represent the geological situation of an area. Here, radon indoor measurements in nearly all homes in three municipalities and its conversion into a radon potential were used to determine the uncertainty of the mean radon potential of an area as a function of the number of investigated homes. It could be shown that the coefficient of variation scales like $1/\sqrt{n}$ with n the number of measured dwellings. The question how to deal with uncertainties when using a classification scheme for the radon risk is discussed and a general procedure is proposed.

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1. Introduction

The EU Basic Safety Standards say in Article 103, Paragraph 3: ‘Member States shall identify areas where the radon concentration (as an annual average) in a significant number of buildings is expected to exceed the relevant national reference level.’ (2013/59/Euratom, 2014). This means the administration has to identify ‘radon priority areas’ (sometimes also called ‘radon-prone areas’) by some classification scheme. In these areas, special attention should be paid to radon during planning and building of new housings. More difficult and therefore more costly will be the identification and subsequently the mitigation of houses with enhanced indoor radon concentration. In most countries, it is considered not economically viable to measure all houses. Therefore, it is necessary to concentrate the investigations on well-defined areas and it is important to have a reliable tool to identify such areas.

As a result of radon surveys areas are usually characterized by mean or median radon concentrations or by a percentage of houses with indoor radon levels exceeding a certain limit or by a Radon Potential (RP) which should represent the geogenic radon hazard. Often these quantities are classified and areas are assigned class levels, e.g. low, medium, high radon risk. In nearly all cases such a classification is derived from radon measurements, which can show a wide variability over spatial units. It is of paramount importance

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to estimate the uncertainties (misclassification probabilities) of such a classification. The classification of e.g. municipalities into different classes of radon risk may have severe consequences for the construction of new buildings in that the strength of provisions for Rn proof construction may depend on the radon risk class of the area in which the building ground lies. Several authors have already investigated the problems connected with such classifications using different approaches (e.g. Piller and Johner, 1998; Price et al., 1996; Gelman and Price, 1999; Miles and Appleton, 2005; Cinelli et al., 2011; Bossew, 2014).

The uncertainty of the mean Rn concentration or RP over an area depends (a) on the true spatial variability of the quantity over that area and (b) on the sampling design which has been applied to estimate the mean, in particular on the *number* of samples. If that number is small and the variability is large (as is normally true for Rn surveys), the chance of a mis-estimation of the mean, and consequently of a mis-classification of the area is high. In this paper a representative selection of sample locations (houses in this case) is assumed, otherwise a bias will be introduced. The selection of sample locations and the proof for representativeness will not be discussed in this paper.

Therefore, it is necessary to investigate the dependence of the uncertainty of any measurement-based categorization on the number of measurements. Such information will help to find a compromise between the number of necessary measurements and therefore costs and the required reliability of the Radon hazard classification of areas.

2. Methods

A survey of indoor radon concentration in about 90% of all houses of three Austrian municipalities (Haibach, Ottenschlag and Reichenau) resulted in a data set sufficiently large for statistical investigations. The measurements were performed by SSNTD with exposure times of approx. 6 months (January/February to July). The Austrian Radon map (Gruber et al., 2015) is based on the RP, which was introduced during the Austrian National Radon Project (ANRP), a country-wide indoors radon survey (Friedmann, 2005). The RP was introduced to normalize different measurement circumstances to a standard situation. It is defined as the indoor radon concentration (in Bq/m^3) in a standard room (annual mean, living room in the ground floor, no basement, and some other fixed parameters). The RP is a conservative standard, in that the standard conditions represent a rather bad situation with respect to indoor Rn. It is derived from indoor measurements by using standardization factors to convert the results of the actual measurement into a hypothetical radon concentration in the assumed standard situation (Friedmann, 2005).

The three investigated municipalities are geologically relatively homogeneous (Seidel et al., 2011). Bed rock is mainly different types of granite. The analysis investigated the probability density distribution of the mean RP as a function of the number of data used to estimate the arithmetic mean (AM) and the geometric mean (GM). For that purpose repeated (10 000) random samples of 3, 6, 12, 24, 48 RP data were taken from all data of one municipality. From these samples, the AM and the GM were computed. As a result the frequency distributions for AM and GM values were computed, with the number of measurements as parameter, i. e. their sampling distributions (Fig. 1). Out of this it is possible to estimate the standard deviations of AM and GM as a function of the number of measurements used to calculate AM and GM. Thus, it is possible to calculate the probability for a misclassification of an area depending on the number of measurements and the distance to the classification boundaries. Similar results can be obtained when using directly the indoor measurement results instead of the RP. However, the distributions become a little bit broader depending on the homogeneity of the data with respect to the controlling factors (e.g. a data set of all measurements at ground floor is more homogeneous than one which includes all floor levels). Similarly, in the case of a classification based on a percentage above a certain limit it is possible to estimate the dependence of the misclassification rate as a function of the number of measurements: Under the assumption of a log-normal distribution with the observed geometric standard deviation the uncertainties of the distribution quantiles follows the uncertainty of the GM and thus imply an uncertainty of the percentage of houses with Rn concentrations above a certain limit.

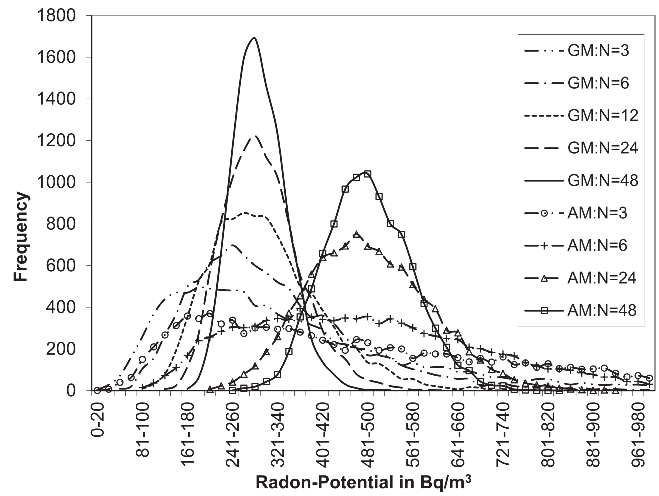

Fig. 1. Frequency distributions: GM (left peak) and AM (right peak) for sample sizes of 3, 6, 12, 24, 48 data from Reichenau.

3. Results

The question was the uncertainty of the mean RP derived from the indoor measurements as a function of the number of investigated dwellings in a certain area. The frequency distributions of the AM and the GM in one of the investigated municipalities (Reichenau) can be seen in Fig. 1. Clearly, the distributions become narrower with increasing sample size, however, the standard deviation remains relatively large. The distributions are asymmetric at low sample sizes and become more symmetric with increasing sample sizes. While individual RP values are close to a log-normal distribution (Hámori et al., 2006; Bossew, 2010; Tondeur and Cinelli, 2014; Cinelli and Tondeur, 2015) reflecting a relatively large number of low values which dominate the distributions for a low number of samples, the AM of a high number of samples approaches an increasingly narrower normal distribution around the AM of all data. This tendency is related to the central limit theorem. A QQ-plot (quantile-quantile-plot) nicely demonstrates this behavior. In Fig. 2 the observed distributions of the AMs from Reichenau (the QQ-plots for the other municipalities look quite similar) are plotted versus the Gaussian distributions defined by the relevant mean and the relevant standard deviation. It can clearly be seen that with increasing sample size the relation becomes more and more linear which means the observed distributions become more and more Gaussian shaped.

Table 1 summarizes the results for all 3 municipalities. There the mean and the standard deviation for different sample sizes are given.

In Fig. 3 the coefficient of variation as a function of the sample size can be seen as well as the relation $y = 1/\sqrt{x}$. The same relation

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